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CONSOLIDATION OF SOFT LAYERS BY FINITE STRAIN ANALYSIS.(U)

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CONSOLIDATION OF SOFT LAYERS BY FINITE STRAIN ANALYSIS

by

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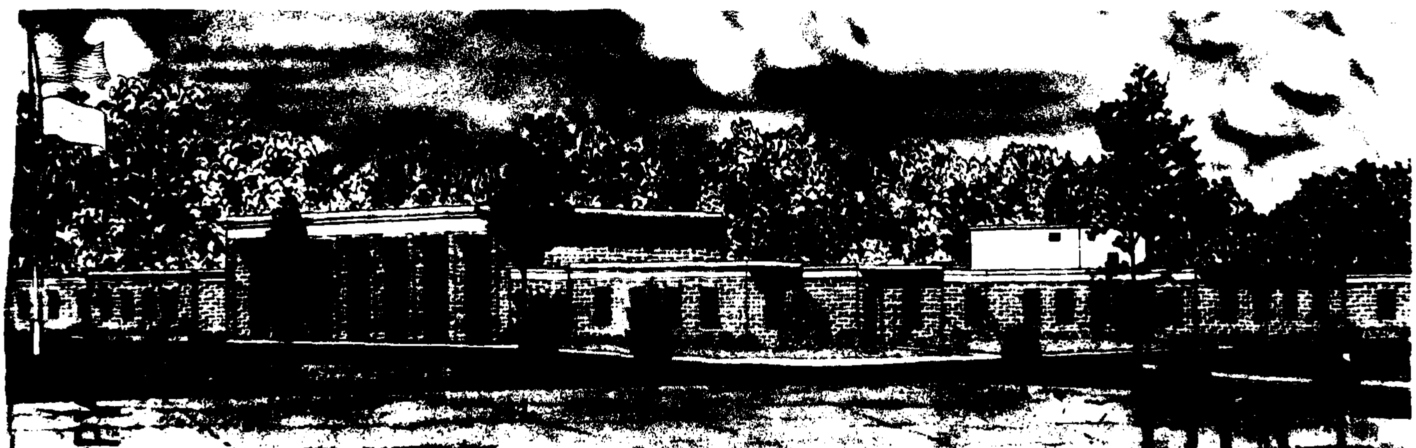
Final Report



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The general theory of one-dimensional finite strain consolidation is developed in terms of the void ratio and time for a moving coordinate system and a material or reduced coordinate system which is time independent. The governing equation is based on fluid continuity and material equilibrium and is totally independent of any restrictions on the form of the void ratio-effective stress and void ratio-permeability relationships. Boundary and initial conditions necessary for equation solution are discussed. Typical initial conditions

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for a normally consolidated layer and a dredged fill layer are illustrated. Boundary conditions for the free-draining, impermeable, and semipermeable interfaces are derived.

A solution of the nonlinear governing equation is derived through the use of an explicit finite difference scheme which preserves the nonlinearity by constantly updating coefficient terms. Solution includes appropriate boundary and initial conditions for any normally consolidated or dredged fill layer. Method of settlement, soil stress, and pore pressure calculation is also given. Conditions necessary for a consistent, stable, and convergent solution are derived in terms of governing equation coefficients.

Equation solution requires laboratory-determined void ratio-effective stress and void ratio-permeability relationships in the form of point values. The determination of these relationships from oedometer testing is discussed. Parameters required for handling semipermeable boundaries are also discussed.

Typical problems involving consolidation of soft layers are solved through use of the computer program CSLFS (Consolidation of Soft Layers, Finite Strain). The first problem involves deposition of multiple layers of dredged fill material on a compressible foundation. The second concerns a soft layer subjected to multiple surcharge loads as would occur through phased construction.

A user's manual for the computer program CSLFS, a program listing, and sample problems are included as Appendixes.

PREFACE

This report was prepared by the Geotechnical Laboratory (GL), U. S. Army Engineer Waterways Experiment Station (WES), as part of CWIS Work Unit No. 31173, "Special Studies for Civil Works Soils Problems," Task 34, Finite Strain Theory of Consolidation, for the Office, Chief of Engineers, U. S. Army. The report and computer program were written by CPT Kenneth W. Cargill under the general supervision of Mr. Clifford L. McAnear, Chief, Soil Mechanics Division (SMD), GL; Dr. William F. Marcuson III, Chief, GL; and Dr. Paul F. Hadala, Assistant Chief, GL.

The Commanders and Directors of the WES during the preparation and publication of this report were COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. Fred R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
inches	0.0254	metres
pounds (force) per square inch	6.894757	kilopascals
pounds (force) per square foot	0.04788026	kilopascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square feet	0.09290304	square metres
tons (force) per square foot	95.76052	kilopascals

CONSOLIDATION OF SOFT LAYERS BY FINITE STRAIN ANALYSIS

PART I: INTRODUCTION

1. The importance of the ability to accurately predict the consolidation behavior of soft clay deposits is manifest in the millions of dollars spent annually in the disposal of materials dredged from the nation's waterways and wastes of the mining industries involved in phosphate and other mineral ore production. To adequately design the catchments necessary to hold these vast quantities, knowledge of the rate of settlement of the clayey material is required. The economics of the disposal operation dictates that each specially constructed area be used to its fullest potential. Therefore, estimating the consolidation in each area is a prerequisite to determining the overall area needed to support a specified application rate.

2. Methods currently available for computing the potential settlements of soft clay deposits as a function of time are based on both empirical and theoretical relationships. This report will deal principally with the theoretical aspects of consolidation and their application to the settlement of soft clay deposits under self-weight loading (although the theory and techniques employed are equally applicable to other types of loading as will be shown in a practical example). It should be noted here that the method to be presented is limited to one-dimensional consolidation of saturated clay deposits which in actuality is no limitation when applied to the large wet disposal sites in current use. Other limitations will be discussed as they apply to particular solution techniques, but in general the theory will require only that the clay deposits be homogeneous in material type.

3. The first theory enabling the prediction of one-dimensional consolidation in soils was published by Karl Terzaghi in 1924. The simplifying assumptions adopted for this original theory were such that its applicability was effectively limited to the consideration of relatively stiff thin layers at large depths. For example, the assumption

that there is a constant relationship between void ratio and effective stress and that permeability does not change within the consolidating material is valid only when the ultimate change in effective stress is small in comparison to the preconsolidation effective stress. Because settlements in soft clay deposits such as dredged fill where strains greater than 50 percent are not uncommon, the assumption of small strains negates the usefulness of Terzaghi's theory unless soil parameters and layer thickness are continuously updated.

4. The usual form of Terzaghi's governing equation (Terzaghi and Peck 1967) is

$$\frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial x^2} \tag{1}$$

where u is the excess pore water pressure and c_v is the coefficient of consolidation. The independent variables are time, t, and the vertical space coordinate, x. Even though this differential equation has limited applicability to the general problem of soil consolidation, it has remained the popular choice among geotechnical engineers because it is the simplest equation and is taught in all basic soil mechanics courses. Solution of the Terzaghi equation is simplified because it is linear and the same as the heat conduction equation for which analytical solutions for a multitude of boundary conditions are available (Carslaw and Jaeger 1959).

5. Many authors have offered alternatives to Equation 1 to better simulate the actual behavior of soils. Schiffman and Gibson (1964) assumed that permeability and the coefficient of volume change were known functions of depth and derived the governing equation as

$$\frac{\partial^2 u}{\partial x^2} + \frac{1}{k}\frac{dk}{dx}\frac{\partial u}{\partial x} = \frac{\gamma_w m_v(x)}{k(x)}\frac{\partial u}{\partial t} \tag{2}$$

where k is permeability, γ_w is unit weight of water, m_v is coefficient of volume change, and other terms are as defined previously. Davis and Raymond (1965) produced a nonlinear theory of consolidation by assuming a constant logarithmic relationship between void ratio and effective stress. Their governing equation is

$$-c_v \left[\frac{1}{\sigma'} \cdot \frac{\partial^2 u}{\partial x^2} - \left(\frac{1}{\sigma'}\right)^2 \frac{\partial u}{\partial x} \frac{\partial \sigma'}{\partial x} \right] = \frac{1}{\sigma'} \frac{\partial \sigma'}{\partial t} \tag{3}$$

where σ' is vertical effective stress and other terms are as previously defined. Other theories or variations include the works of McNabb (1960) and Mikasa (1965). However, all of these variations to the original Terzaghi equation have their own unique limitations and are not suited for application to large deposits of soft dredged fill or mine tailings.

6. While the equations of McNabb and Mikasa did allow for large strains, the first completely general theory of one-dimensional consolidation in soils was published by Gibson, England, and Hussey in 1967. Their governing equation, which will be fully developed in the next section, is

$$\left(\frac{\gamma_s}{\gamma_w} - 1\right) \frac{d}{de} \left[\frac{k(e)}{1 + e}\right] \frac{\partial e}{\partial z} + \frac{\partial}{\partial z} \left[\frac{k(e)}{\gamma_w (1 + e)} \frac{d\sigma'}{de} \frac{\partial e}{\partial z}\right] + \frac{\partial e}{\partial t} = 0 \tag{4}$$

where γ_s is the unit weight of solids, e is void ratio, z is a material coordinate to be explained later, and other terms are as defined previously. The consolidation equation in this form is particularly suited for application to thick soft clay deposits because it intrinsically includes the effects of self weight, permeability varying with void ratio, and a nonlinear void ratio-effective stress relationship. It also is independent of the degree of strain which is the key reason it is suitable for thick soft clay deposits susceptible to large settlements. Hereinafter, Equation 4 will be referred to as the finite strain theory while Equation 1 and its variations will be referred to as the small strain theory.

7. The fact that Equation 4 is a completely general theory of one-dimensional consolidation was demonstrated by Schiffman (1980) when he showed that the small strain theory and its principal linear and nonlinear variations are all special cases of the finite strain theory. Practical application of the theory and a comparison of results with those

of the small strain theory were presented by Gibson, Schiffman, and Cargill (1981). Using conventional laboratory data for a soft marine deposit, they demonstrated that faster and larger settlements are predicted by finite strain theory although predicted dissipation of excess pore water pressure may be slower than that predicted by the small strain theory.

8. The next part of this report will document the development of the finite strain theory governing equation along with the initial and boundary conditions necessary for its solution. The solution technique to be employed is an explicit finite difference scheme which will then be illustrated in a manner suitable for computer programming. The computer program CSLFS (Consolidation of Soft Layers, Finite Strain) will be used to solve a practical dredge fill consolidation problem and a soft foundation consolidation problem to illustrate the capabilities of the program. A user's manual for CSLFS is included in Appendix A.

PART II: FINITE STRAIN FORMULATION OF ONE-DIMENSIONAL CONSOLIDATION

9. The basic assumptions necessary for the development of the theory of one-dimensional finite strain consolidation are:

<u>a</u>. The soil system is saturated and consists of a compressible soil matrix and incompressible pore fluid. While the soil matrix is considered compressible, individual soil particles are incompressible.

<u>b</u>. Pore fluid flow velocities are small and governed by Darcy's law.

<u>c</u>. There is a unique relationship between soil permeability and void ratio such that

$$k = k(e) \tag{5}$$

<u>d</u>. There is a unique relationship between vertical effective stress and void ratio such that

$$\sigma' = \sigma'(e) \tag{6}$$

<u>e</u>. The material is homogeneous as to type.

These conditions are only slightly restrictive and imply monotonic loading. The usual assumption made in the small strain theory restricting the magnitude of strain is not made here.

Coordinate System

10. The election to allow unlimited strain makes the use of a fixed coordinate system impractical due to the relatively large movement of the top boundary of the consolidating layer. To simplify the required mathematics, a coordinate system which moves with the layer is needed. This condition is satisfied when the coordinates are defined in terms of the volume of solid particles in the layer, which happens to be a constant quantity. These material or reduced coordinates (Ortenblad 1930) are uniquely suited for use in the time-dependent consolidation

problem because they are time independent and independent of the amount of strain.

11. Before material coordinates can be employed, however, a relationship must be established between these coordinates and the more conventional methods of thickness measurement. Consider the soil element shown within the consolidating layer in Figure 1. At time $t = 0$ the initial configuration is given in what will be called Lagrangian coordinates. This system is related to "real" measurements at $t = 0$. For time, t, during the consolidation process, "real" measurements are made in terms of a convective coordinate system which is a function of the Lagrangian coordinate and time.

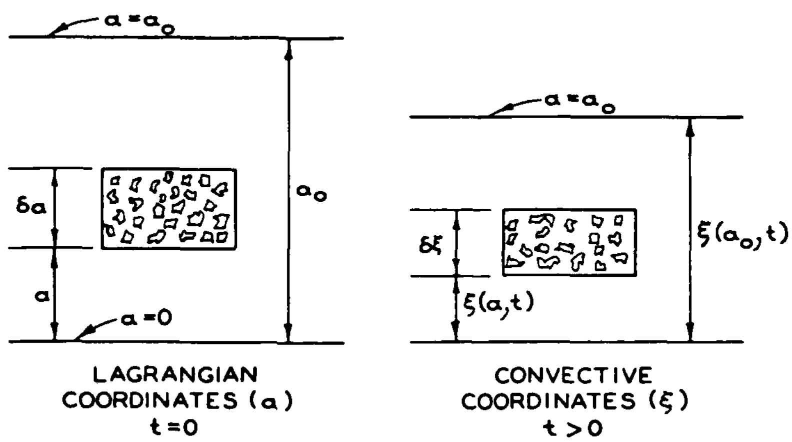

Figure 1. Coordinate systems

12. Both Lagrangian and convective coordinates are a measurement of the soil system, which includes both solid soil particles and the pore fluid. As previously stated, the material coordinate is a measure of the volume of solid particles only. A comparison of these three systems is illustrated in Figure 2. As shown in the illustration, only the Lagrangian and material coordinates are constant for all time for particular points in the soil layer. It is, therefore, convenient to develop the governing equation in terms of either of these systems. The material coordinates will be used here.

13. Since material coordinates are not measurable in the usual

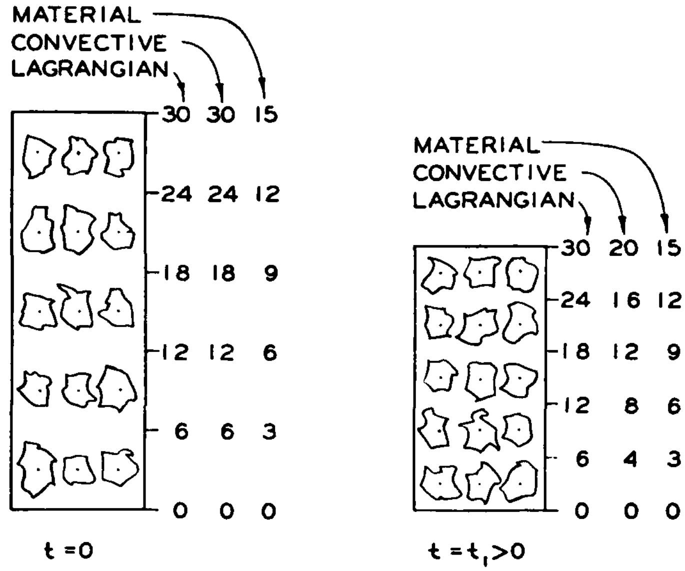

Figure 2. Comparison of coordinate systems

sense, it is necessary to develop a method of conversion from one coordinate system to another so that the layer thickness may be expressed in easily understood conventional units at any time. Consider the differential elements of soil shown in Figure 3. If these elements are chosen

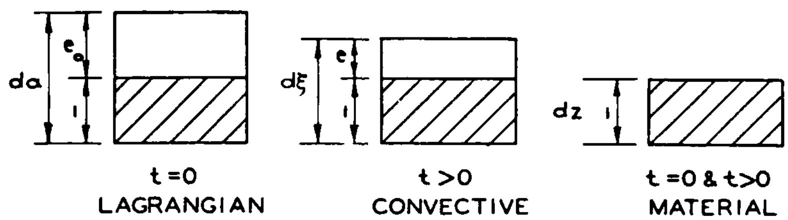

Figure 3. Differential soil elements

such that they encompass a unit volume of solid particles, then

$$da = 1 + e_o \tag{7}$$

$$d\xi = 1 + e \tag{8}$$

and

$$dz = 1 \tag{9}$$

where e_o is the initial void ratio and e is the void ratio at some later time during consolidation. By simple ratios

$$\frac{dz}{da} = \frac{1}{1 + e_o} \tag{10}$$

$$\frac{d\xi}{dz} = 1 + e \tag{11}$$

and

$$\frac{d\xi}{da} = \frac{1 + e}{1 + e_o} \tag{12}$$

Thus conversion from one coordinate system to another can be accomplished by simple integration such that

$$z = \int_0^a \frac{da}{1 + e(a,0)} \tag{13}$$

and

$$\xi = \int_0^z [1 + e(z,t)]\ dz \tag{14}$$

These relationships will be used extensively throughout the remainder of this development so that equilibrium and continuity conditions may be expressed in the most easily understood manner and then transformed into the material coordinate system for the governing equation.

Material Equilibrium

14. The equilibrium of a soil element having unit area

perpendicular to the page and a unit volume of solid particles is illustrated in Figure 4. The weight, W, of the element is the sum of the

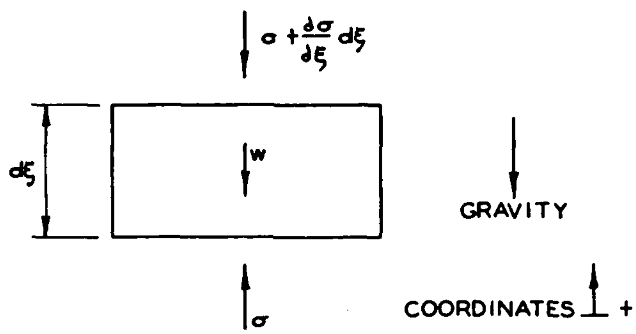

Figure 4. Soil element in equilibrium

weights of pore fluid and solid particles:

$$W = e\,\gamma_w + (1)\,\gamma_s \tag{15}$$

Therefore, equilibrium of the soil mixture is given by

$$\sigma + \frac{\partial \sigma}{\partial \xi} d\xi + (e\,\gamma_w + \gamma_s) - \sigma = 0 \tag{16}$$

where σ is the total stress. By simplifying and applying Equation 8, an equation relating the spatial rate of change in total stress to the void ratio and unit weights of solids and fluid is obtained:

$$\frac{\partial \sigma}{\partial \xi} + \frac{e\,\gamma_w + \gamma_s}{1 + e} = 0 \tag{17}$$

Multiplying through by $\frac{d\xi}{dz}$ and substituting Equation 11 gives the equilibrium equation in terms of material coordinates:

$$\frac{\partial \sigma}{\partial z} + e\,\gamma_w + \gamma_s = 0 \tag{18}$$

15. It is also necessary to derive an expression for the equilibrium of the pore fluid alone. Considering the total fluid pressure at any time to be composed of both a static and excess pressure gives

$$u_w = u_o + u \tag{19}$$

where u_w, u_o, and u are total, static, and excess pressures, respectively. Static pressure equilibrium is ensured if

$$\frac{\partial u_o}{\partial \xi} + \gamma_w = 0 \tag{20}$$

Therefore, differentiation of Equation 19 yields

$$\frac{\partial u_w}{\partial \xi} - \frac{\partial u}{\partial \xi} + \gamma_w = 0 \tag{21}$$

or in terms of the material coordinate

$$\frac{\partial u_w}{\partial z} - \frac{\partial u}{\partial z} + \gamma_w(1 + e) = 0 \tag{22}$$

Fluid Continuity

16. To determine the equation of continuity for the fluid phase of the differential soil element, the weight of fluid inflow minus the weight of fluid outflow is equated to the time rate of change of weight of fluid stored in the element. As shown in Figure 5, the weight of fluid flowing into the volume is

$$n \cdot v \cdot \gamma_w \tag{23}$$

per unit area where n is the volume porosity which is here assumed also the area porosity and v is the velocity of flow. Since the soil solid particles are also moving during consolidation,

$$v = v_f - v_s \tag{24}$$

where subscripts f and s represent fluids and solids, respectively.

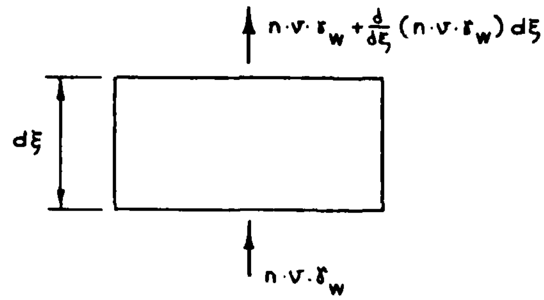

Figure 5. Fluid flow through a differential element

The weight of fluid outflow is

$$n \cdot v \cdot \gamma_w + \frac{\partial}{\partial \xi} (n \cdot v \cdot \gamma_w) d\xi \qquad (25)$$

By specifying the differential element to have a unit volume of solid particles, the weight of fluid contained within the element is

$$e \ \gamma_w \qquad (26)$$

and its time rate of change is therefore

$$\frac{\partial}{\partial t} (e \ \gamma_w) \qquad (27)$$

Equating this time rate of change of the weight of fluid within an element to inflow minus outflow results in

$$\frac{\partial}{\partial \xi} [n(v_f - v_s)] \ d\xi + \frac{\partial e}{\partial t} = 0 \qquad (28)$$

where the fluid is assumed incompressible and thus has a constant unit weight which is cancelled in the equation.

17. Equation 28 is the equation of continuity expressed in terms of the convective coordinate system. Utilizing the chain rule for differentiation, the relationship

$$\frac{\partial F}{\partial z} = \frac{\partial F}{\partial \xi}\frac{d\xi}{dz} \tag{29}$$

can be written where F is any function. Equations 8, 11, and 29 can be applied and Equation 28 can then be written as

$$\frac{\partial}{\partial z}\left[n(v_f - v_s)\right] + \frac{\partial e}{\partial t} = 0 \tag{30a}$$

or

$$\frac{\partial}{\partial z}\left[\frac{e(v_f - v_s)}{1 + e}\right] + \frac{\partial e}{\partial t} = 0 \tag{30b}$$

since

$$n = \frac{e}{1 + e} \tag{31}$$

Governing Equation

18. Before a governing equation can be assembled, two other relationships are needed. The first is the well-known effective stress principle

$$\sigma = \sigma' + u_w \tag{32}$$

and the next is the equally well-known Darcy's law which is usually written in the form

$$n(v_f - v_s) = -\frac{k}{\gamma_w}\frac{\partial u}{\partial \xi} \tag{33}$$

Equations 21 and 31 can be used and this can be written in terms of total fluid pressure and the void ratio as

$$\frac{e(v_f - v_s)}{1 + e} = -\frac{k}{\gamma_w}\left(\frac{\partial u_w}{\partial \xi} + \gamma_w\right) \tag{34}$$

By Equations 29 and 11, this becomes

$$e(v_f - v_s) = -\frac{k}{\gamma_w}\left[\frac{\partial u_w}{\partial z} + \gamma_w(1 + e)\right] \tag{35}$$

19. Now Equations 18, 30b, 32, and 35 can be united to produce a governing equation. First, combine Equation 30b and 35 to eliminate the velocity terms. Thus

$$\frac{\partial}{\partial z}\left[-\frac{k}{\gamma_w(1 + e)}\left(\frac{\partial u_w}{\partial z} + \gamma_w + e\,\gamma_w\right)\right] + \frac{\partial e}{\partial t} = 0 \tag{36}$$

Next, use Equation 32 to eliminate u_w in Equation 36

$$\frac{\partial}{\partial z}\left[-\frac{k}{\gamma_w(1 + e)}\left(\frac{\partial \sigma}{\partial z} - \frac{\partial \sigma'}{\partial z} + \gamma_w + e\gamma_w\right)\right] + \frac{\partial e}{\partial t} = 0 \tag{37}$$

and then Equation 18 to eliminate σ in Equation 37

$$\frac{\partial}{\partial z}\left[-\frac{k}{\gamma_w(1 + e)}\left(-\gamma_s - \frac{\partial \sigma'}{\partial z} + \gamma_w\right)\right] + \frac{\partial e}{\partial t} = 0 \tag{38a}$$

or

$$\left(\frac{\gamma_s}{\gamma_w} - 1\right)\frac{\partial}{\partial z}\left(\frac{k}{1 + e}\right) + \frac{\partial}{\partial z}\left[\frac{k}{\gamma_w(1 + e)}\frac{\partial \sigma'}{\partial z}\right] + \frac{\partial e}{\partial t} = 0 \tag{38b}$$

Again, by the chain rule of differentiation, the relationship

$$\frac{\partial F}{\partial z} = \frac{dF}{de}\frac{\partial e}{\partial z} \tag{39}$$

can be written and Equation 38b thus becomes Equation 4:

$$\left(\frac{\gamma_s}{\gamma_w} - 1\right)\frac{d}{de}\left[\frac{k(e)}{1 + e}\right]\frac{\partial e}{\partial z} + \frac{\partial}{\partial z}\left[\frac{k(e)}{\gamma_w(1 + e)}\frac{d\sigma'}{de}\frac{\partial e}{\partial z}\right] + \frac{\partial e}{\partial t} = 0 \tag{4}$$

which is the same as the previous Equation 4 and constitutes the governing equation of one-dimensional consolidation in terms of the void ratio, e, and the functions $k(e)$ and $\sigma'(e)$.

20. An analytical solution to Equation 4 is not possible, but once appropriate boundary conditions are specified, its numerical

solution is feasible with the aid of a computer. Of course, the relationships between permeability and void ratio and effective stress and void ratio must also be known or assumed.

Boundary Conditions

21. Three types of boundary conditions are possible for a soft clay deposit undergoing consolidation. These are shown in Figure 6 with

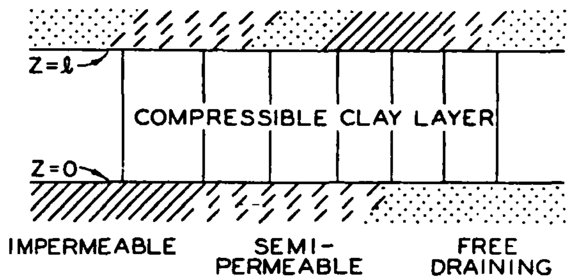

Figure 6. Possible boundary conditions

possible combinations at the top and bottom of the layer. The condition of semipermeable is an addition to the usually assumed conditions of either permeable or impermeable. The semipermeable condition represents the state when a compressible layer is in contact with another different compressible layer or when a compressible layer is in contact with an incompressible layer which has neither the characteristics of a free-draining layer nor those of an impermeable layer, but something in between.

22. For the case of a free-draining boundary, there is no excess fluid pressure and the total fluid pressure is equal to the static pressure

$$u_w = u_o = h_w \gamma_w \tag{40}$$

where h_w is the height of the free water table above the boundary. Since the total weight of material above the boundary is known, total stress may be calculated, and by the effective stress principle, effective stress can be calculated. The void ratio is then deduced from the known or assumed relationship between it and effective stress.

23. At an impermeable boundary, there is no fluid flow and thus

$$v_f = v_s \tag{41}$$

Applying this to Equation 35 results in

$$\frac{\partial u_w}{\partial z} + \gamma_w(1 + e) = 0 \tag{42}$$

but consideration of Equation 32, the effective stress equation, gives

$$\frac{\partial \sigma}{\partial z} - \frac{\partial \sigma'}{\partial z} + \gamma_w(1 + e) = 0 \tag{43}$$

Now if Equation 18 is used to replace the total stress term and the relationship of Equation 39 is used to express the effective stress part in terms of the void ratio, Equation 43 can be written

$$\frac{\partial e}{\partial z} + \frac{\gamma_s - \gamma_w}{\frac{d\sigma'}{de}} = 0 \tag{44}$$

which is the boundary condition where the compressible layer meets an impermeable layer.

24. The boundary condition for a semipermeable layer is based on the fact that the quantity of fluid flowing out of one layer must equal the quantity of fluid flowing into the layer across their common boundary. The quantity of fluid flowing across a boundary of unit area is

$$n(v_f - v_s) \tag{45}$$

Therefore

$$[n(v_f - v_s)]_{upper} = [n(v_f - v_s)]_{lower} \tag{46}$$

where the subscripts indicate upper and lower layers. Then from Equation 33 and the relationship of Equations 29 and 11

$$\left(\frac{k}{1+e}\frac{\partial u}{\partial z}\right)_1 = \left(\frac{k}{1+e}\frac{\partial u}{\partial z}\right)_2 \tag{47}$$

where γ_w is eliminated because the same fluid is in both layers and 1 and 2 indicate upper and lower layers, respectively. It should also be noted that the total, static, and therefore excess fluid pressures must be equal in the two layers at their common boundary

$$(u)_1 = (u)_2 \tag{48}$$

25. From the effective stress principle,

$$\frac{\partial \sigma}{\partial z} - \frac{\partial u_w}{\partial z} = \frac{\partial \sigma'}{\partial z} \tag{49}$$

By use of the equilibrium conditions of Equations 18 and 22, Equation 49 can be rewritten as

$$\frac{\partial \sigma'}{\partial z} = \gamma_w - \gamma_s - \frac{\partial u}{\partial z} \tag{50}$$

which can also be written

$$\frac{\partial e}{\partial z} = \left(\gamma_w - \gamma_s - \frac{\partial u}{\partial z}\right)\frac{de}{d\sigma'} \tag{51}$$

The conditions expressed by Equations 47, 48, and 51 may be used to allow numerical solution to the problem of semipermeable boundaries.

Initial Conditions

26. Initial conditions through a compressible layer will vary according to the stress history of the layer. Since it is necessary to solve the governing equation by an approximate numerical technique, any initial distribution of void ratios is permissible so long as it is

consistent with the assumed void ratio versus effective stress relationship. Typical inital void ratio distributions in qualitative terms are as follows:

a. A dredged fill layer will have a high uniform initial void ratio distribution.

b. A layer consolidated under self weight only will have relatively high initial void ratios which decrease considerably with depth in the layer.

c. A layer normally consolidated under a small surcharge load will have intermediate void ratios which decrease with depth.

d. A layer consolidated under a large surcharge load or overconsolidated will have relatively low initial void ratios which decrease only slightly with depth.

The value of these void ratios and their exact distribution will depend on the void ratio-effective stress relationship chosen and any existing surcharge.

PART III: SOLUTION OF THE GOVERNING EQUATION

27. An analytical solution of the one-dimensional finite strain governing equation is not possible because of the nonlinear nature of its coefficients. However, a numerical solution of the equation is feasible if these coefficients are constantly updated during the solution to simulate their nonlinearity. An explicit finite difference scheme has been chosen to solve the equation because of its relatively simple algorithm, but this scheme does necessitate stringent stability criteria which will be discussed in a later section.

Explicit Finite Difference Scheme

28. The finite difference procedure is a method of representing a differential term by means of finite differences. Time space is broken down into intervals of finite length denoted τ . The time derivative of void ratio can then be written

$$\frac{\partial e}{\partial t}(z_i, t_j) \cong \frac{1}{\tau}(e_{i,j+1} - e_{i,j}) \tag{52}$$

where the subscripted terms are as shown in Figure 7. If the space

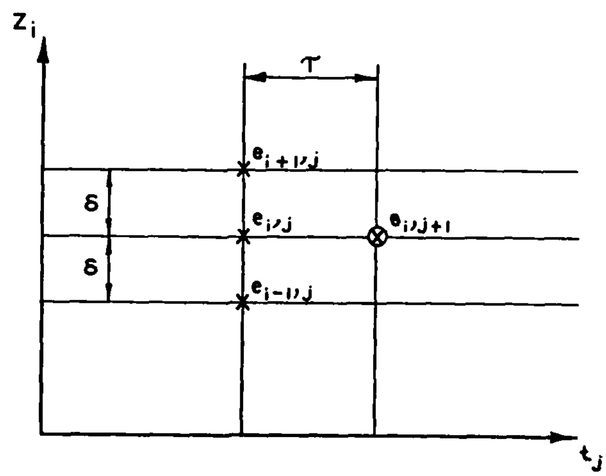

Figure 7. Finite difference mesh

coordinate is divided into intervals denoted δ , the derivative of void ratio with respect to space is

$$\frac{\partial e}{\partial z}(z_i, t_j) \cong \frac{1}{2\delta}(e_{i+1,j} - e_{i-1,j}) \tag{53}$$

by the central difference method, and the second derivative of void ratio with respect to space is

$$\frac{\partial^2 e}{\partial z^2}(z_i, t_j) \cong \frac{1}{\delta^2}(e_{i+1,j} - 2e_{i,j} + e_{i-1,j}) \tag{54}$$

where terms are also as shown in Figure 7.

Simulation of Nonlinearity

29. It is appropriate here to rewrite the general governing equation (Equation 4) in the form

$$\left\{\gamma_c \beta(e) + \frac{\partial}{\partial z}[\alpha(e)]\right\} \frac{\partial e}{\partial z} + \alpha(e) \frac{\partial^2 e}{\partial z^2} + \gamma_w \frac{\partial e}{\partial t} = 0 \tag{55}$$

where

$$\gamma_c = \gamma_s - \gamma_w \tag{56}$$

$$\beta(e) = \frac{d}{de}\left[\frac{k(e)}{1 + e}\right] \tag{57}$$

and

$$\alpha(e) = \frac{k(e)}{1 + e} \frac{d\sigma'}{de} \tag{58}$$

To simulate the equation nonlinearity, the functions $\alpha(e)$ and $\beta(e)$ are recalculated at each time step for the current value of the void ratio at each point in the z space grid.

30. In the computer program developed for this report, point data are input relating void ratio to permeability and effective stress

similar to that which would be obtained from laboratory testing. To ensure smooth continuous functions, however, additional points are inserted between the laboratory determined points. A typical trace of such data is shown in Figure 8. Using these data, tables of values for $\alpha(e)$ and $\beta(e)$ at various values of e can be constructed by numerical differentiation. Then, by a linear interpolation, the value of $\alpha(e)$ and $\beta(e)$ for any value of e can be obtained.

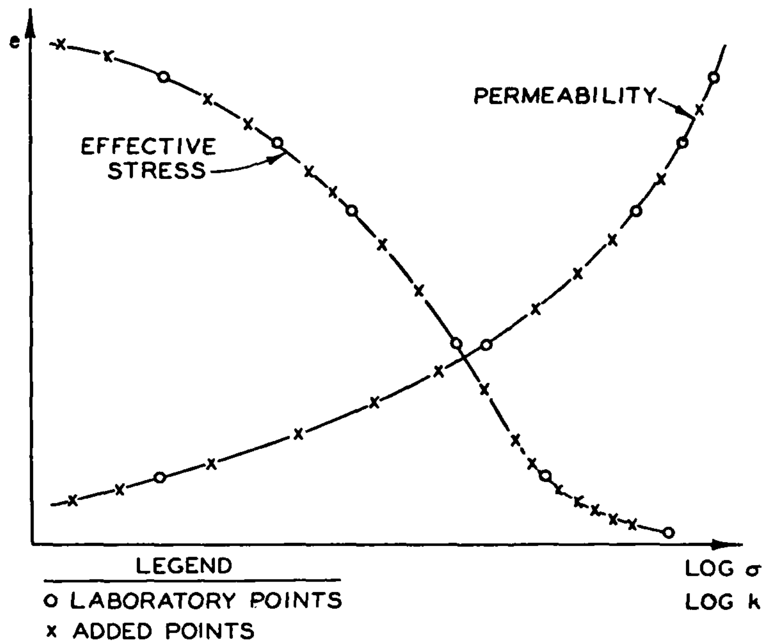

Figure 8. Typical plot relating void ratio, e , to permeability, k , and effective stress, σ'

31. The solution to the governing equation in finite differences can now be written

$$e_{i,j+1} = e_{i,j} - \frac{\tau}{\gamma_w}\left(\left\{\gamma_c \beta(e_{i,j}) + \left[\frac{\alpha(e_{i+1,j}) - \alpha(e_{i-1,j})}{2\delta}\right]\right\}\left[\frac{e_{i+1,j} - e_{i-1,j}}{2\delta}\right] + \alpha(e_{i,j})\left[\frac{e_{i+1,j} - 2e_{i,j} + e_{i-1,j}}{\delta^2}\right]\right) \tag{59}$$

From Equation 59 it is seen that the void ratio along point z_i at a future time, t_{j+1} , is explicitly determined from the values of the void ratio at that point and its nearest neighbors at time t_j and functions of the void ratio at these same points at the present time, t_j . Thus, once initial and boundary conditions are determined, the consolidation problem is solved.

Solution for Initial Conditions

32. Calculation of the initial void ratio distribution in a compressible layer is dependent on the unit weights of solids and fluid in the layer, the effective weight of any existing surcharge, and the relationship between void ratio and effective stress within the layer. To illustrate the procedure, assume the compressible and saturated layer shown in Figure 9 is fully consolidated under its own self weight only

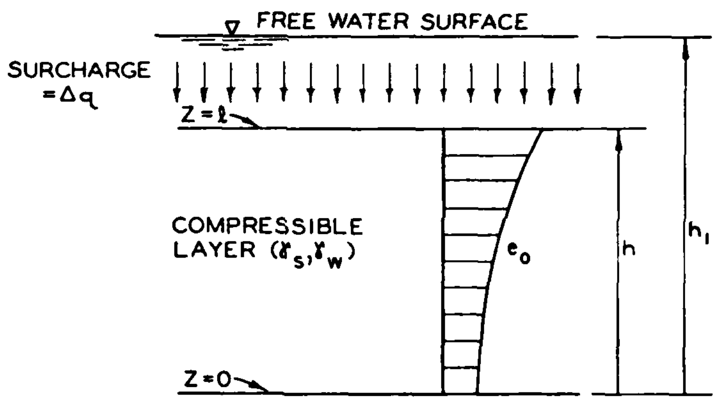

Figure 9. Initial void ratio distribution in a compressible layer consolidated under self weight only

before a surcharge, Δq , is added which will cause further consolidation. The initial conditions in the layer at $t = 0^+$ are then the same as conditions in the layer at $t = 0^-$ assuming the surcharge is quickly added at $t = 0$. This is so because the fluid in the layer has not had time to drain, and therefore, initially, fluid pressure will support all the added surcharge. Of course, as time goes by the surcharge load will gradually be transferred to the soil particles causing the solid skeleton to compress.

33. To determine the initial void ratio distribution, $e_o(a)$, the equation

$$\int_o^{\ell} dz = \int_o^{h} \frac{da}{1 + e_o(a)} = \ell \tag{60}$$

must be solved where h is the initial layer height in Lagrangian coordinates and ℓ is the initial height in material coordinates. Since there are two unknowns in this equation, it cannot be solved without some additional information. In a fully consolidated state, the effective stress distribution through a layer depends only on the buoyant weight of solids and any existing surcharge such that

$$\sigma'(z,o) = \int_z^{\ell} (\gamma_s - \gamma_w) dz + q_o \tag{61}$$

When Equations 60 and 61 are used in conjunction with the relationship between void ratio and effective stress such as that shown in Figure 8, the number of relationships matches the number of unknowns and solution is possible. However, even if the relationship between void ratio and effective stress were expressed analytically and the appropriate substitutions made in Equations 60 and 61, a transcendental equation would result which would require an iterative type solution. Therefore, an incremental technique will be used here which will approach the exact solution from the lower side.

34. It is first necessary to divide the compressible layer into a number of elemental layers of length

$$\Delta a = \frac{h}{N} \tag{62}$$

where N is any positive integer. The larger the N, the more accurate the solution. The uppermost elemental layer is subject to an effective stress equal to the effective weight of any existing surcharge, q_o. When this effective weight is used, a void ratio is obtained from data such as Figure 8. This void ratio is assumed constant for the elemental layer. Therefore, for the first layer

$$\Delta z(1) = \frac{\Delta a}{1 + e_o(1)} \tag{63}$$

and

$$\Delta\sigma'(1) = (\gamma_s - \gamma_w)\Delta z(1) + q_o \tag{64}$$

When $\Delta\sigma'(1)$ is used as the effective stress acting on the second incremental element, the void ratio of the second element can be determined. Following this technique throughout the entire layer results in the initial void ratio distribution sufficiently accurate for computation of future consolidation.

35. For the case of a dredged fill, it is assumed that the layer is deposited at a uniform consistency, and after initial solids sedimentation the compressible layer exists at a uniform void ratio with zero effective stress throughout the layer. Under these conditions, total layer height in material coordinates is calculated directly from

$$\ell = \frac{h}{1 + e_o} \tag{65}$$

where h is the height of the compressible layer after initial sedimentation but before any consolidation.

Void Ratio at Boundaries

36. Void ratio calculation at a free-draining boundary is actually a calculation of effective stress at the boundary. This calculation is done through a knowledge of the total weight of materials above the boundary plus any existing or added surcharge and the distance of the boundary below the free water surface. Since there is no excess fluid pressure, the effective stress is

$$\sigma' = \sigma + \Delta q - \gamma_w h_w \tag{66}$$

where σ is the total stress due to any existing surcharge and material self weight, Δq is an added surcharge, and h_w is distance of the boundary below the free water surface. With this effective stress, the persistent void ratio can then be determined from a relationship such as shown in Figure 8.

37. The determination of void ratio at an impermeable boundary requires the use of a fictitious mesh point outside the boundary as shown in Figure 10. Using the initial void ratio distribution or distribution at any time, t_j , the void ratio at this fictitious mesh point is calculated by expressing Equation 44 in finite difference terms. Thus

$$e_{0,j} = e_{2,j} + 2\delta\left(\frac{de}{d\sigma'}\right)_{e_{1,j}} (\gamma_s - \gamma_w) \tag{67}$$

where $\frac{de}{d\sigma'}$ is determined for $e_{1,j}$ from data such as in Figure 8. With $e_{0,j}$ determined, $e_{1,j+1}$ is then found from Equation 59 and the whole process repeated at each time step.

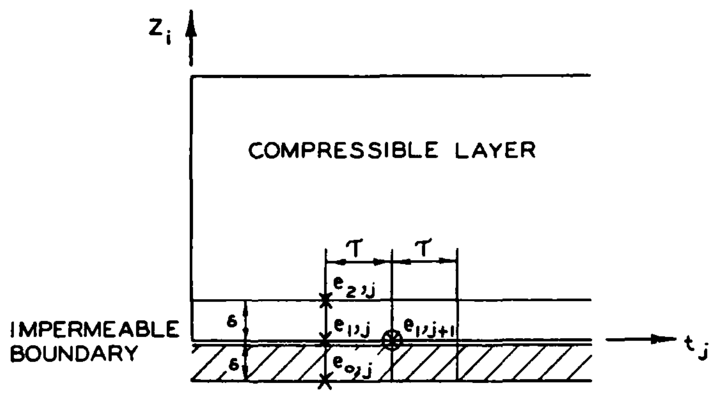

Figure 10. Void ratio calculation at an impermeable boundary

38. When a compressible layer lower boundary is neither free draining nor impermeable, void ratio calculation at the boundary is accomplished by writing a finite difference expression for Equation 51 and using an imaginary mesh point as was done for the impermeable case. Then,

$$e_{0,j} = e_{2,j} + 2\delta\left(\frac{de}{d\sigma'}\right)_{e_{1,j}} \left[\gamma_s - \gamma_w + \left(\frac{\partial u}{\partial z}\right)_{1,j-1}\right] \qquad (68)$$

where the term $\frac{\partial u}{\partial z}$ is either calculated from the previous time step or assumed. In the case of a dredged fill overlying a compressible layer, the excess pressure gradient at the layer interface is assumed to be zero for the first time step and thereafter it is calculated based on the previous conditions and Equations 47 and 48. The procedure is shown schematically in Figure 11. The method of calculating excess pressure

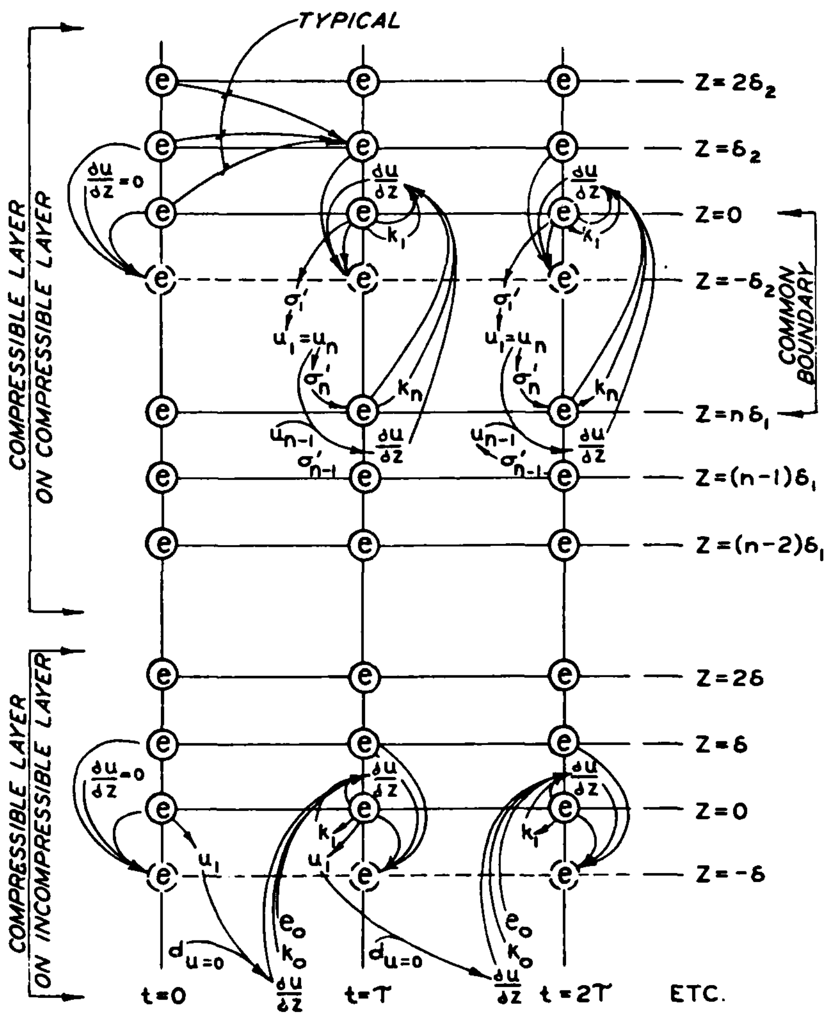

Figure 11. Schematic representation of void ratio calculation at semipermeable boundaries

from void ratio and vice versa is given in a later section. The void ratio of the top point in the compressible lower layer is based on Equation 48 and the fact that the change in excess pore pressure equals the negative change in effective stress. In the case of a compressible layer overlying a semipermeable incompressible layer, the permeability, void ratio, and a typical drainage path length in the incompressible layer must be either measured or assumed. The calculation procedure is also illustrated in Figure 11. Only a typical illustration of marching forward in time is shown, but this holds for all void ratios except at the imaginary points and the top point in a compressible foundation layer.

Settlement Calculation

39. The calculation of settlement at any point in a compressible layer is simply the subtraction of its convective coordinate from its Lagrangian, or initial, coordinate. If settlement at a point is denoted $S(z,t)$, then

$$S(z,t) = a(z,0) - \xi(z,t) \tag{69}$$

and by integration of Equations 10 and 11

$$S(z,t) = \int_0^z [1 + e(z,0)]dz - \int_0^z [1 + e(z,t)]dz \tag{70}$$

Since data are generated aroun mesh points in the finite difference solution of the consolidation problem, the numerical integration of Equation 70 by Simpson's rule is a simple exercise.

40. A common method of expressing the state of consolidation in small strain theories is by the percentage of excess pore pressure dissipated. In the finite strain theory, degree of consolidation is appropriately defined as the ratio of current settlement to final settlement in the entire layer. Thus

$$U_t = \frac{S(\ell,t)}{S(\ell,\infty)} \tag{71}$$

where $S(\ell,\infty)$ is the ultimate settlement of the layer when all excess pore pressure has dissipated.

Calculation of Stresses and Pressures

41. Once the void ratio distribution throughout a compressible layer is determined, the distribution of effective stress can be obtained from a relationship such as shown in Figure 8. The static pore pressure is also immediately determined for each mesh point as

$$u_o(z,t) = \gamma_w[h_1 - \xi(z,t)] \tag{72}$$

where h_1 is the height of the free water surface above the datum plane, $z = 0$, and ξ is the convective coordinate of the mesh point at the time in question.

42. The total stress at a point in the compressible layer is equal to the total weights in a unit area of all materials above it plus any surcharge. Thus

$$\sigma(z,t) = \gamma_w\left[h_2 + \int_z^{\ell} e(z,t)dz\right] + \gamma_s\left(\int_z^{\ell} dz\right) + q_o \tag{73}$$

where h_2 is the height of the free water surface above the top $(z = \ell)$ of the compressible layer, the integrals represent the volumes of fluid and solids in the compressible layer, respectively, and q_o is any surcharge.

43. With total and effective stresses determined, the effective stress principle is used to calculate total pore pressure

$$u_w(z,t) = \sigma(z,t) - \sigma'(z,t) \tag{74}$$

and excess pore pressure is the difference between total and static pressures,

$$u(z,t) = u_w(z,t) - u_o(z,t) \tag{75}$$

Solution Consistency, Convergence, and Stability

44. Now that a solution technique for solving the finite strain consolidation problem has been formulated, some assurance that this technique gives a correct answer is necessary. Consistency implies that the difference equations actually do approximate the differential equation. Convergence means that the numerical solution is a close approximation of the exact solution. Stability implies that small errors introduced initially or at a boundary remain bounded as the computations progress. Keller (1960) has shown that for a parabolic partial differential equation of the form

$$\frac{\partial e}{\partial t} - a(z,t)\frac{\partial^2 e}{\partial z^2} - 2b(z,t)\frac{\partial e}{\partial z} + c(z,t)e = d(x,t) \tag{76}$$

consistency, convergence, and stability are assured in an explicit finite difference scheme if

$$\delta \le \frac{a(z,t)}{|b(z,t)|} \tag{77}$$

and

$$\tau \le \frac{1}{\frac{2a(z,t)}{\delta^2} + c(z,t)} \tag{78}$$

where δ and τ are the spatial and time mesh spacings, respectively, and a , b , and c are any variables.

45. In the governing Equation 55 for finite strain consolidation

$$a(z,t) = -\frac{\alpha(e)}{\gamma_w} \tag{79}$$

$$b(z,t) = -\frac{1}{2\gamma_w}\left\{\gamma_c\ \beta(e) + \frac{\partial}{\partial z}\ [\alpha(e)]\right\} \tag{80}$$

$$c(z,t) = 0 \tag{81}$$

$$d(z,t) = 0 \tag{82}$$

where $\alpha(e)$ and $\beta(e)$ are as previously defined in Equations 58 and 57, respectively. Therefore, if

$$\delta \leq -\frac{2\alpha(e)}{\gamma_c\ \beta(e) + \frac{\partial}{\partial z}\ [\alpha(e)]} \tag{83}$$

and

$$\tau \leq -\frac{\delta^2\ \gamma_w}{2\alpha(e)} \tag{84}$$

then the solution should be consistent, convergent, and stable. To ensure these criteria are met throughout the solution process, Equations 83 and 84 should be periodically checked using the extreme values of $\alpha(e)$ and $\beta(e)$ to be expected in the problem.

PART IV: SOIL PARAMETERS FOR FINITE STRAIN CONSOLIDATION

46. Calculation of the consolidation of soft deposits by finite strain theory requires the determination of the specific gravity of solids in the compressible layer, the relationship between void ratio and effective stress, and the relationship between void ratio and permeability. These determinations are presently routine laboratory procedures for fine-grained soils normally encountered in earth construction. The use of standard oedometer tests for soft deposits which may be underconsolidated in situ involves uncertainties; for instance, a thin oedometer sample with no excess pore pressure and subjected to a sudden load increment may not react in the same way as an underconsolidated thick sample whose excess pore pressure is slowly decreased. Additionally, the consolidation induced by the hydraulic gradient of a permeability test may not be adequately accounted for in the test results. The answers to these questions are beyond the scope of this report and need research to either relate soft deposit parameters to the results of conventional tests or devise new test methods so that direct measurements can be made.

47. In order to demonstrate the use of the computer program CSLFS, the soil parameters necessary were deduced from conventional oedometer test data such as may be generated in any well equipped soils testing facility. By logical extrapolation of these data generated by the oedometer testing over the full range of void ratios that might be encountered, reasonable solutions to the dredged fill consolidation problem can be obtained. Of course, the test results on a thick normally consolidated or overconsolidated soil under a surcharge should be directly applicable without extrapolation.

48. Use of the program feature enabling the specification of boundary conditions that are neither free draining nor impermeable requires that a void ratio, permeability, and drainage path length for the incompressible foundation material be given. While it is generally possible to determine void ratio and permeability by laboratory testing on undisturbed samples, the distance required for dissipation of excess

pore pressures in the incompressible foundation must be estimated based on engineering judgment.

Void Ratio-Effective Stress Relationship

49. The conventional laboratory oedometer test can be used to establish the void ratio-effective stress relationship required for calculation of consolidation by finite strain theory subject to the uncertainties previously raised. Principally, the only difference between testing soft deposits and the stiffer soils usually tested is in the size of the load increments used. For routine tests of most soils, the loading schedule starts at 0.25 tsf* and is doubled for each succeeding increment until a total load of 16.0 tsf is applied. Typical tests of soft deposits such as channel sediments or dredged fill start at 0.012 tsf and are incrementally increased to 1.0 tsf. At these extremely low pressures, accurate account must be taken of the weights of load transfer hardware and even the force exerted by dial gage springs (Palermo, Montgomery, and Poindexter 1978).

50. Perhaps the best method of graining insight into the behavior of soft clay soils is to examine some typical oedometer test results. In Figures 12 and 13 are plotted $e\text{-}\log \sigma'$ curves as determined in the Soils Testing Facility at the U. S. Army Engineer Waterways Experiment Station. These plots have been corrected from the originally reported results (Palermo, Shields, and Hayes in press) by assuming 100 percent saturation at test completion. This was necessary because direct measurements of the specific gravity of soil solids were not made and original results consistently indicated saturation greater than 100 percent when average specific gravity values were assumed.

51. Figure 12 shows four samples taken from the Craney Island dredged material disposal site, one sample of channel sediments considered typical of what goes into the disposal area, and one sample of

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units of measurement is found on page 5.

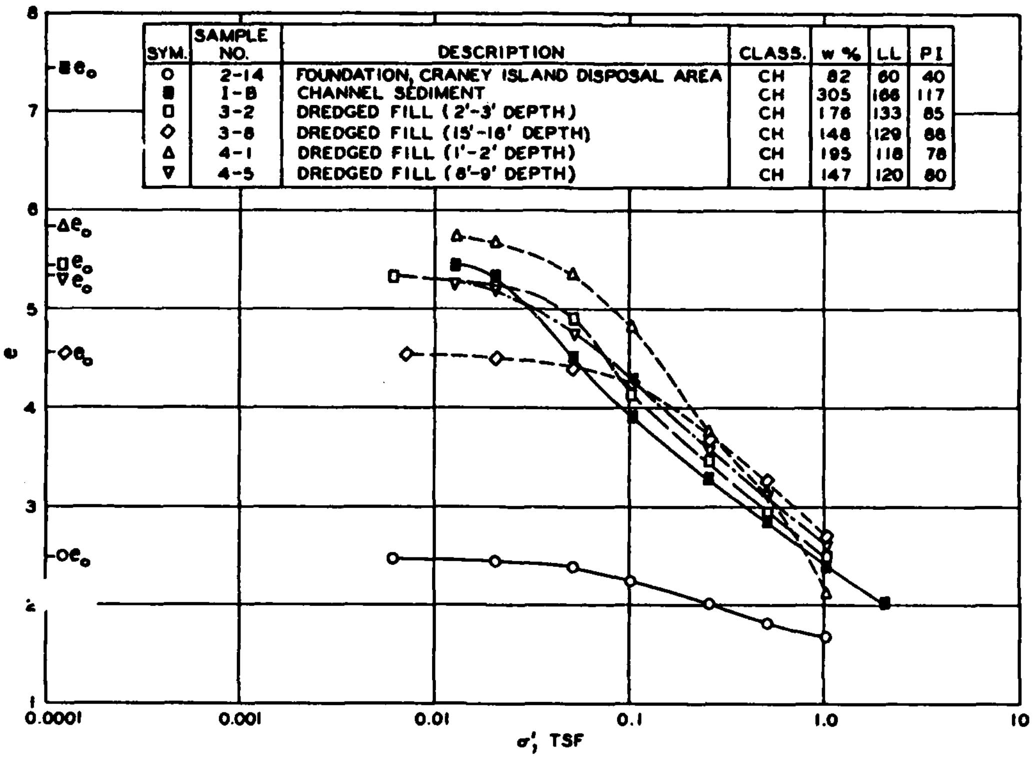

Figure 12. Oedometer test results for Craney Island samples

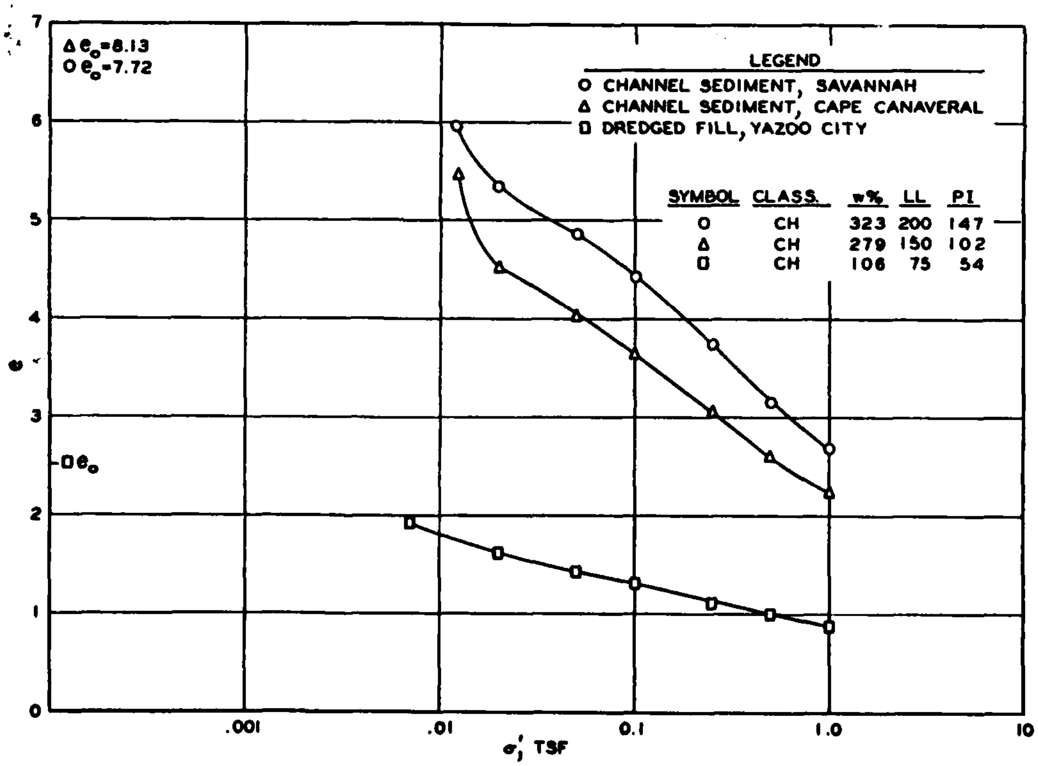

Figure 13. Oedometer test results for other samples

the foundation soil beneath the disposal area. As can be seen from the figure, these soft deposits generally have characteristics similar to other soils encountered in construction practice except that the range of void ratios these deposits undergo during consolidation is much greater. The tendency for initial void ratios to increase as in situ confining stresses decrease is also apparent from the figure. A conventional analysis to determine the preconsolidation pressure from the e-log σ' curves is probably not appropriate since there is no way to obtain a truly undisturbed sample of such soft soils. However, the normally consolidated portion of the curves should be a valid indication of the soil behavior as indicated by the fact that all dredged material curves including that for channel sediments are approximately parallel over their normally consolidated range.

52. Consolidation characteristics of other soft materials are shown in Figure 13. Here again, the extremely wide variation in void ratios over relatively small stress ranges should be noted. The unusual upturn in these curves at the low end of the stress range may be peculiar to the particular test procedure or may be valid indicators of the behavior of these materials. Definite conclusions cannot be drawn without further testing.

53. To illustrate the method of obtaining the necessary void ratio-effective stress relationship for use in the computer program CSLFS, consider the data points as shown in Figure 12. It is proposed that those points defining the normally consolidated portions of the e-log σ' curves fully describe the material behavior between effective stresses of about 0.01 tsf to 1.0 tsf. Defining the curve below and above these values is a matter of judgment in the absence of experimental evidence dictating otherwise. The arbitrary extension of the normally consolidated portion in a straight line is unreasonable since this would give an infinite void ratio at zero effective stress and a zero void ratio at some finite effective stress. Probably a more reasonable assumption is that there will be some finite void ratio at zero effective stress and that the curve will become asymptotic to some minimum void ratio depending on the origins of the soil. It is therefore further proposed

that the void ratio at zero effective stress be selected as somewhere between the void ratio at the intersection of the normally consolidated line with the effective stress ordinate 0.001 tsf and the measured void ratio before oedometer testing. The curve at effective stresses higher than 1.0 tsf should ideally be based on oedometer testing at these higher stresses, but in the absence of such data may reasonably be an extension of the normally consolidated portion which is brought asymptotic to a constant void ratio value between 0.4 and 0.7. Figure 14 shows such curves constructed from the data of Figure 12. Void ratios of 7.0 for the dredged fill and 3.0 for the foundation soil at zero effective stress were chosen as about midway between the previously proposed range of possibilities.

54. Before the final decision is made to use such a void ratio-effective stress relationship in the computer program CSLFS, the curve

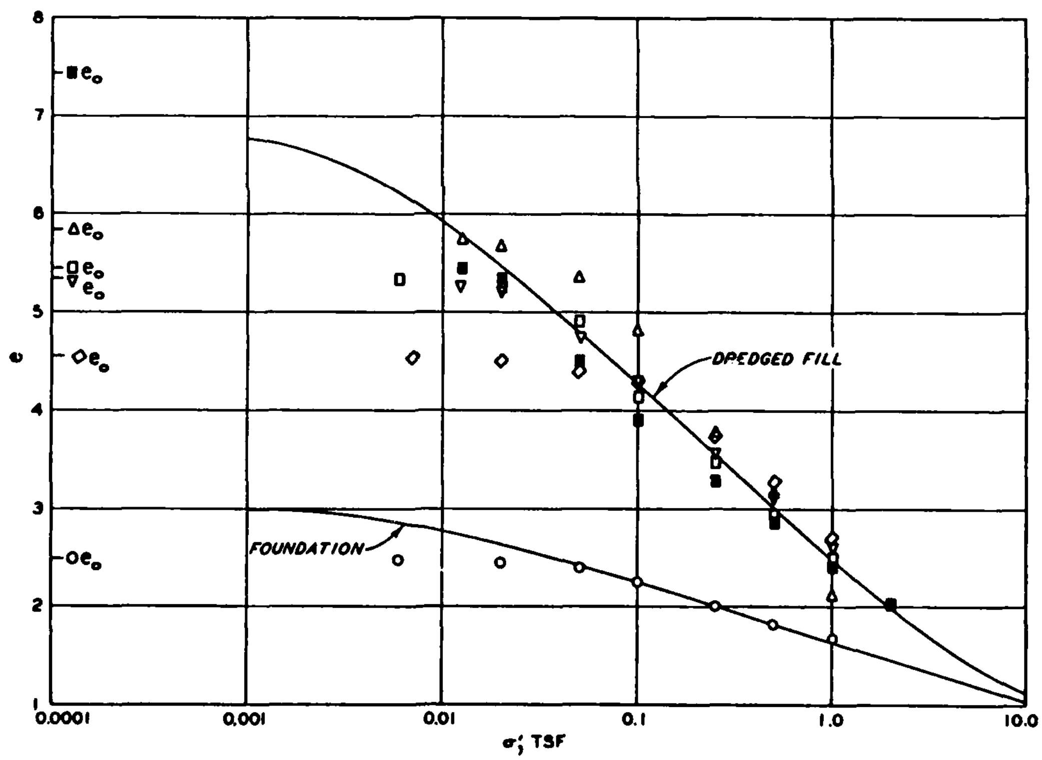

Figure 14. Void ratio-effective stress relationships for soft dredged fill and foundation materials at Craney Island

should be replotted on an arithmetic scale to ensure the curve is a smooth continuous function without extraneous reverse curvature and with continuous derivatives. Figure 15 shows such a plot for the dredged fill material, and Figure 16 shows the plot for the foundation soil from the Craney Island site. The points shown on the plots are the points to be used as program input for a practical example to be worked.

Void Ratio-Permeability Relationship

55. The determination of the void ratio-permeability relationship necessary for calculation of consolidation by the computer program CSLFS will also be accomplished through use of oedometer test results. Because conventional oedometer testing involves relatively thin samples and relatively small load increments, analysis of this testing based on the assumptions of small strain consolidation theory will probably produce sufficiently accurate values of permeability.

56. By small strain theory, a nondimensional time factor is defined by

$$T = \frac{c_v t}{H^2} \tag{85}$$

where t is real time, H is the drainage path length, and the coefficient of consolidation, c_v, is

$$c_v = \frac{k(1 + e)}{\gamma_w a_v} \tag{86}$$

where k is permeability, e is void ratio, and γ_w is unit weight of water as previously defined. The coefficient of compressibility, a_v, is defined as

$$a_v = -\frac{\Delta e}{\Delta \sigma'} \tag{87}$$

where Δe is the change in void ratio corresponding to the change in effective stress, $\Delta\sigma'$. Combining the three preceding equations

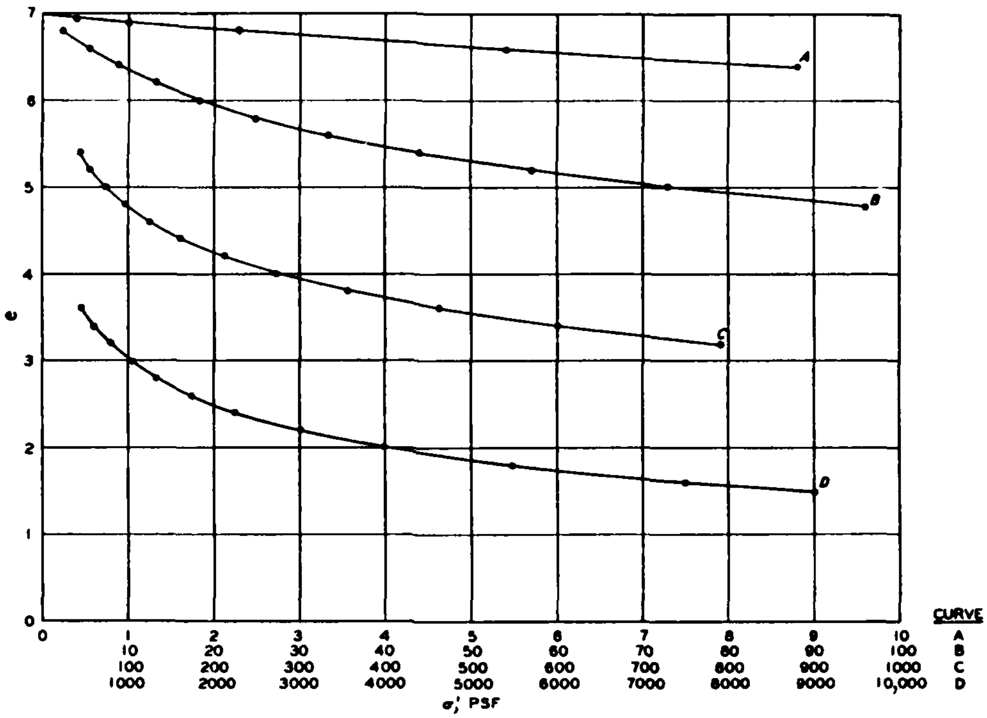

Figure 15. Void ratio-effective stress relationship for soft dredged fill to be used in computer program CSLFS

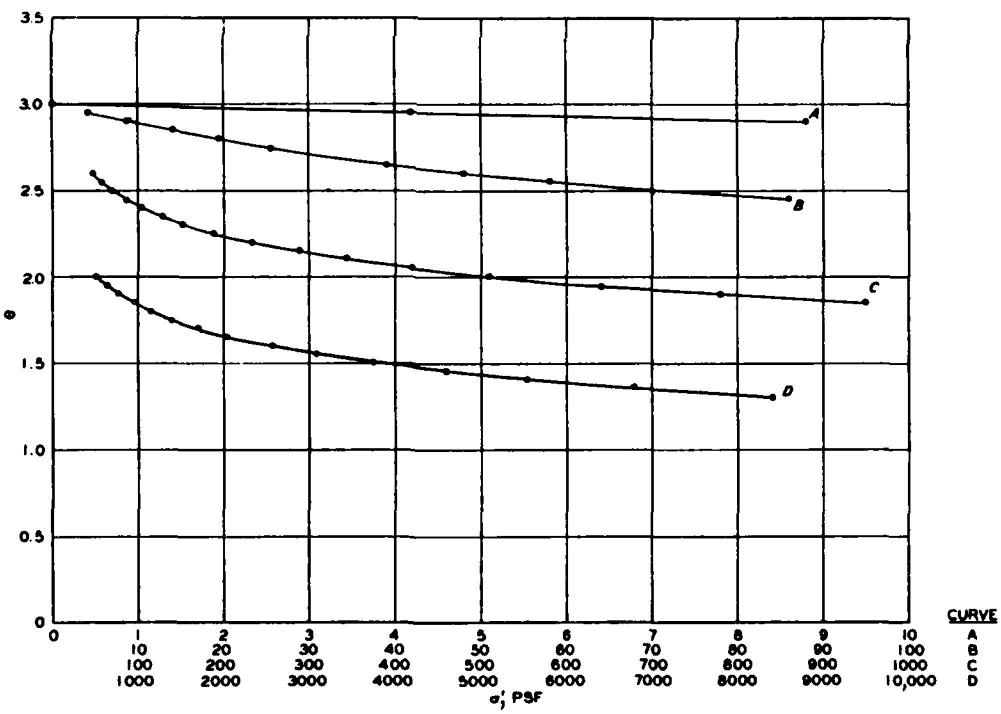

Figure 16. Void ratio-effective stress relationship for foundation soil to be used in computer program CSLFS

results in an expression for permeability,

$$k = - \frac{T \gamma_w \Delta e H^2}{(1 + e) t \Delta\sigma'} \tag{88}$$

which involves known or measurable quantities in the oedometer test.

57. Typically, consolidation time curves for each load increment are used to determine the time, t, for 50 percent consolidation where analytically $T = 0.197$ for an initial uniform distribution of excess pore water pressure. The void ratio, e, is also determined at t_{50} from a knowledge of the specific gravity of solids, total weight of solids, and current sample volume. The drainage path length, H, is estimated as one-half the sample height at t_{50}. An average coefficient of compressibility is obtained by dividing the total void ratio change during the load increment by the load increment.

58. Permeabilities determined in this manner for the foundation soil and dredged fill of the Craney Island disposal site are shown in Figure 17. While the data at the higher void ratios is considerably scattered, the data in the lower void ratios which is less scattered does seem to give a good fit when extended. Here again, the behavior of the void ratio-permeability relationship outside the range of data points is purely speculative until such time as adequate testing is devised and used in defining the curve over the full range of possible void ratios. However, it is probably reasonable to assume that permeability becomes infinitesimally small at some finite void ratio and thus the curve will become asymptotic to this void ratio.

59. Figure 18 shows the relationship between void ratio and permeability for the same other samples of soft deposits described previously in Figure 13. The behavior of these curves at the higher void ratios may be an idiosyncrasy of the test procedure since it is probably more reasonable to expect that permeability would increase more dramatically as the void ratio reached some maximum limit where the soil no longer forms an interconnected network of solid particles.

60. As before, it is beneficial to plot the void ratio-permeability

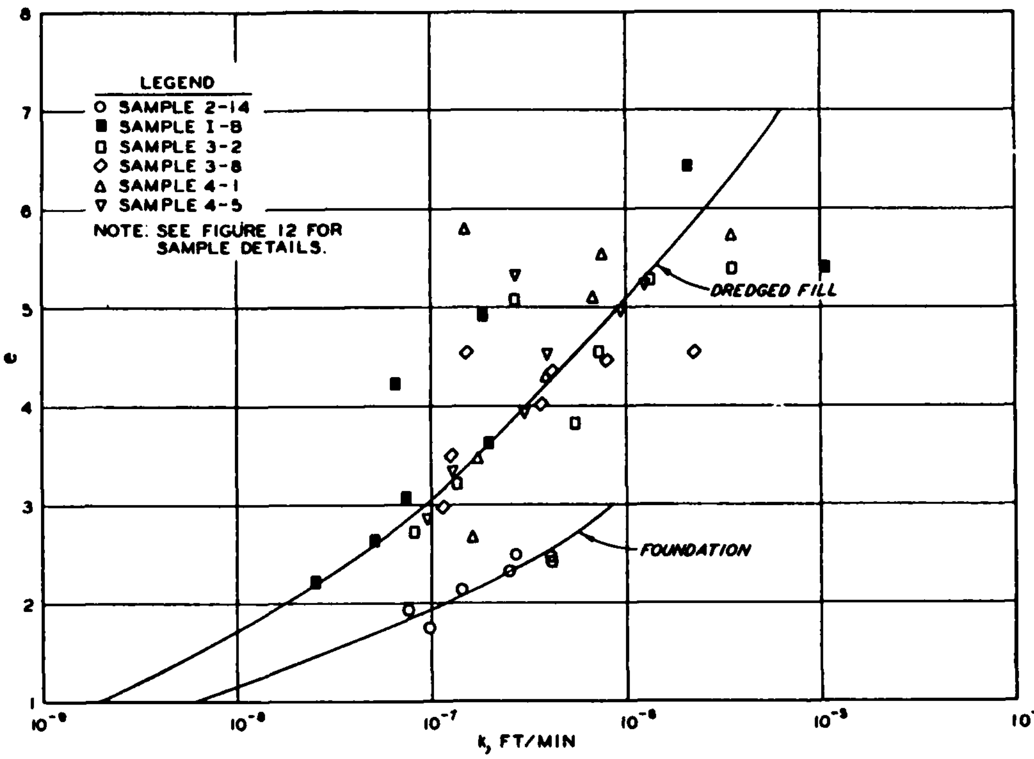

Figure 17. Void ratio-permeability relationships for soft dredged fill and foundation materials at Craney Island

relationship on an arithmetic scale as an aid in determining the point data for use in the program CSLFS. Figure 19 shows such a plot for the dredged fill material, and Figure 20 is of the foundation soil at the Craney Island Site. The points shown on the figures are the points to be used as program input for a practical example.

Semipermeable Boundary Parameters

61. As previously shown, the boundary conditions between two compressible layers undergoing consolidation are automatically determined by the program CSLFS based on the continuity of fluid flow and current void ratio and permeability conditions in the compressible layers. Where a compressible layer bounds an incompressible layer, boundary conditions are determined by the program based on current conditions in the

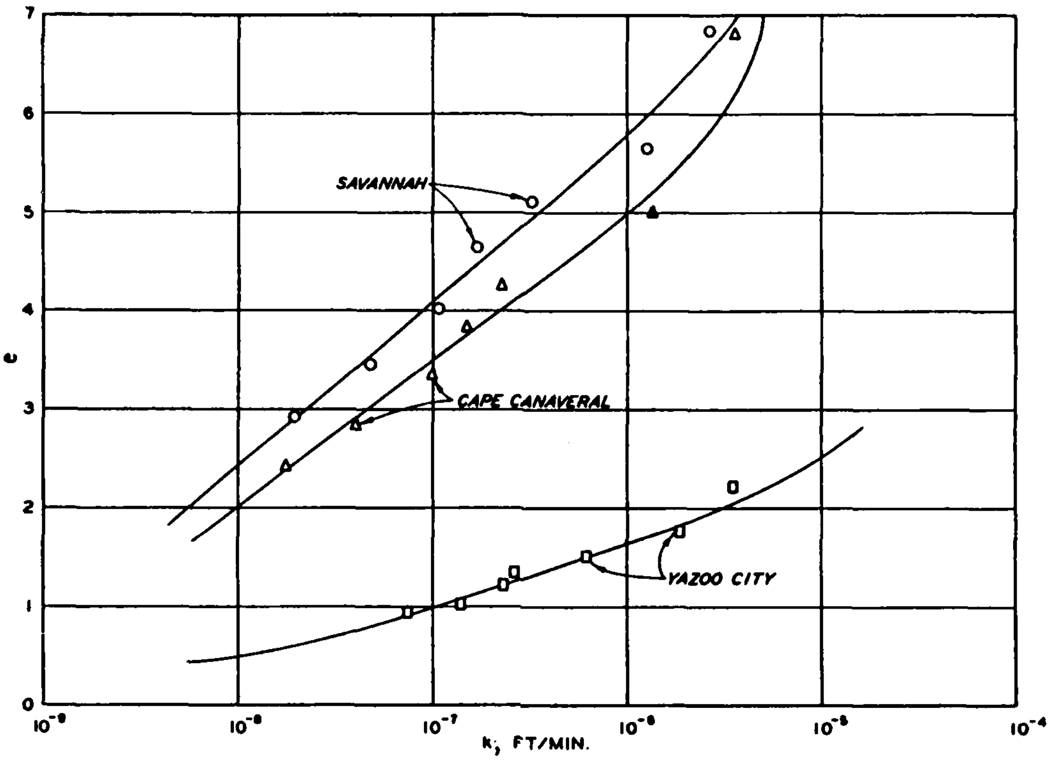

Figure 18. Void ratio-permeability relationship for other samples

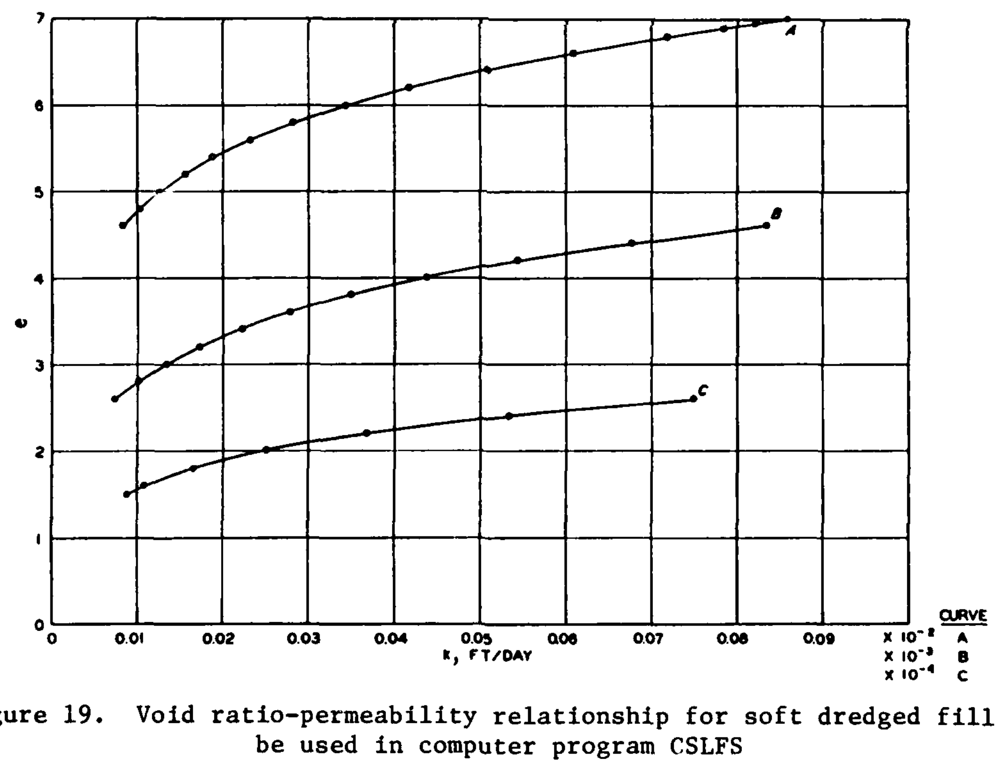

Figure 19. Void ratio-permeability relationship for soft dredged fill to be used in computer program CSLFS

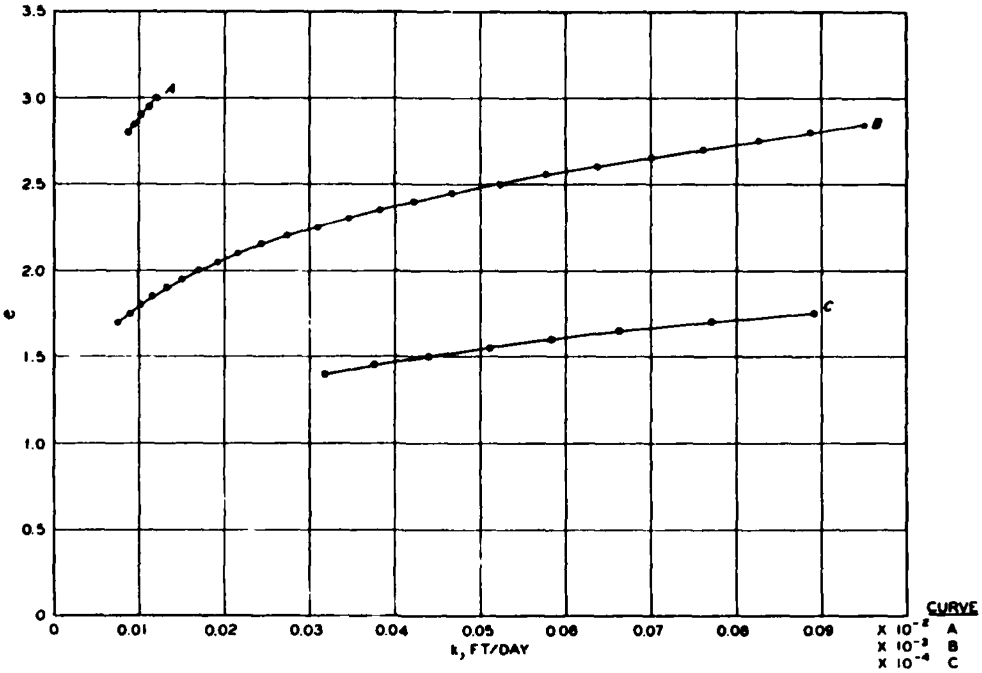

Figure 20. Void ratio-permeability relationship for foundation soil to be used in computer program CSLFS

compressible layer and specified void ratio, permeability, and length of drainage path for the incompressible layer. It was also previously stated that the void ratio and permeability for the incompressible layer should generally be determined by laboratory testing on undisturbed samples and that specification of the drainage path length is a matter of engineering judgment. The basis for making such a judgment is discussed in this section.

62. The drainage path length is defined as that distance required for complete dissipation of excess pore water pressure existing at the layer boundary. Together with this pore pressure, it is used to determine the excess pressure gradient at the incompressible layer side of the boundary by the equation

$$\frac{\partial u}{\partial z} = \frac{u}{\dfrac{x}{1 + e}} \tag{89}$$

where u is the excess pore pressure at the boundary, x is the drainage path length measured in the Lagrangian coordinate system, and e is the void ratio of the incompressible layer. The excess pore pressure is calculated as previously described from the void ratio of the compressible layer. The pressure gradient thus obtained is used in Equation 47 to determine the excess pore pressure gradient on the compressible layer side of the boundary as

$$\left(\frac{\partial u}{\partial z}\right)_{comp} = \left(\frac{1 + e}{k}\right)_{comp} \left(\frac{k}{1 + e} \frac{\partial u}{\partial z}\right)_{incomp} \tag{90}$$

where the subscripts comp and incomp refer to the compressible layer and the incompressible layer, respectively. This value is then used in Equation 68 for computing the void ratio of an image point which enables the computation of the void ratio at the first mesh point in the compressible layer at the next time step.

63. An examination of Equation 89 shows that if the drainage path length is chosen to be very large, the effect is to make $\frac{\partial u}{\partial z}$ very small and in the limit will approach zero or the impermeable boundary condition which makes Equation 68 the same as Equation 67. At the other extreme, if the drainage path length is chosen to be very small, the effect is to make $\frac{\partial u}{\partial z}$ very large and in the limit will approach an infinite value. The computation in Equation 68 then has no physical meaning, but the effect in the program is to cause the void ratio at the first mesh point in the compressible layer to be set at its final value or the free-draining boundary condition.

64. Between those conditions of impermeable and free draining, it is proposed that the drainage path length be chosen to equal the depth of the compressible layer where the material of the incompressible layer is the same or essentially the same as that of the compressible layer. Where the material properties are substantially different, it is further proposed that the drainage path length be chosen to be proportional to the ratios of the permeability functions times the depth of the compressible layer. In equation form, this means

$$x = \left[\frac{\left(\frac{k}{1 + e} \right)_{comp}}{\left(\frac{k}{1 + e} \right)_{incomp}} \right] h \tag{91}$$

where x is the drainage path length, h is the depth of compressible material, and k and e are average permeability and void ratio, respectively, in the respective layers near the interface of the layers.

PART V: CONSOLIDATION PROBLEMS

65. In this Part, the capabilities of the computer program CSLFS will be demonstrated by solving some practical examples involving the consolidation occurring in a dredged fill disposal site subjected to periodic deposition of soft channel sediments and the consolidation of a thick soft layer subjected to an additional surcharge due to some construction activity above it. Figures will be used to show the distributions of excess pore pressure, void ratio, layer settlement versus time, and percent consolidation versus time. Whenever possible, a comparison between the results computed by the finite strain formulation will be compared with those from a small strain theory computation.

Consolidation of Dredged Fill on a Compressible Foundation

66. In this example, a large disposal site has been proposed for an area of a bay where foundation material is a soft marine sediment currently about 5 ft below mean sea level. Considerations of the area available for disposal and the volume and type of material to be dredged has led to the conclusion that the site must be capable of holding material deposited according to the following schedule:

Year 1 through Year 2, 3 ft/year
Year 3 through Year 4, 2 ft/year
Year 5 through Year 8, 1 ft/year

The total amount for each year will be deposited during the first few weeks of each year and therefore can be considered to be dumped instantaneously in the disposal area at the beginning of each year. Figure 21 shows the schedule graphically. It should also be noted that the yearly amounts are based on volumes after initial sedimentation has taken place. If initial sedimentation is not complete very soon after each particular dredging operation, due consideration of the nonsedimented height of each layer must be taken into account when calculating the necessary height of confinement dikes.

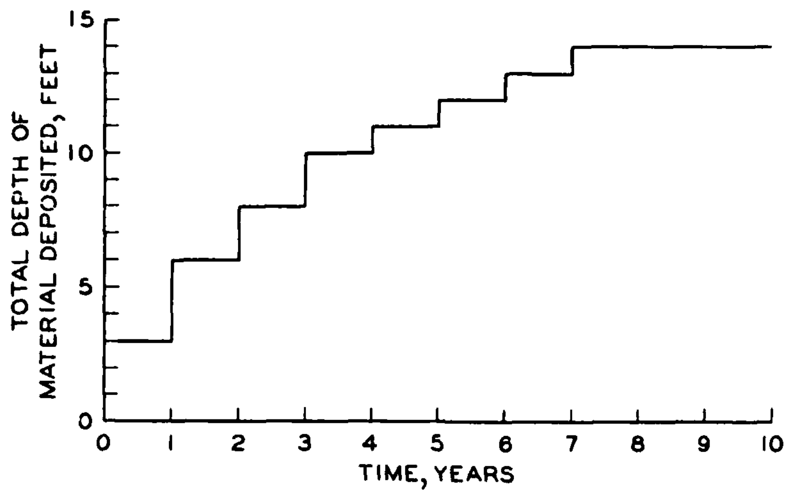

Figure 21. Schedule of dredged material deposition

67. The consolidation behavior of these dredged fill deposits is required to be calculated in conjunction with the consolidation behavior of the foundation in order that a program of dike construction may be instituted that is neither overly conservative nor extravagant. It is further required that an estimate be made of the time required for 90 percent consolidation of the disposal area and ultimate settlement so that an evaluation of its potential future use may be made.

68. Before consolidation can be calculated, laboratory determinations must be made of the void ratio-effective stress and void ratio-permeability relationships for both the dredged and foundation materials along with the unit weight of solids in these materials and the initial void ratio assumed by the dredged material after initial sedimentation. For this example, the relationships depicted in Figures 15, 16, 19, and 20 will be used. The dredged material is assumed to have an initial void ratio of 7.0 and a specific gravity of solids of 2.75. The foundation is assumed to have a specific gravity of solids of 2.83 and to be normally consolidated under its own weight.

69. It will be further assumed that field borings were additionally used to determine that the compressible foundation is 20.0 ft thick and overlays an incompressible layer of silty material having an average

void ratio of 0.65 and permeability of 3.0×10^{-4} ft/day. The void ratio and permeability of the compressible foundation layer at the interface with the incompressible silt deposit could be determined either by field borings or by assuming the layer is normally consolidated under its own weight and allowing the computer program to calculate its initial conditions. For this example a void ratio of 1.80 and permeability of 1.03×10^{-4} ft/day have been chosen based on program calculations. Equation 91 is used to determine the drainage path length for this semi-permeable boundary as about 6.0 ft.

70. The input data required for problem solution is shown in Appendix C of this report. The calculation constants τ and δ are chosen small enough so that problem detail and accuracy are preserved, yet large enough to promote computation economy. If the constants are too large for the stability criteria, the program will print an error message. For this problem, $\tau = 1.0$ day and δ is one-sixth of the initial layer height for the dredged fill and one-tenth for the foundation. These selections proved sufficient for accuracy and stability. Also included in the appendix is calculated data for the end of the second and eighth year of consolidation.

71. From these calculated data, a visual picture of the consolidation process can be obtained. Figure 22 shows the void ratio distribution in the dredged fill at the end of year 2 after two layers of fill have been placed but before the third layer is placed. Also shown in the figure are the void ratio distribution at year 1 after the second layer is placed (which serves as the initial conditions for the current consolidation period) and the final void ratio distribution if no more dredged fill layers were to be placed. In the figure, void ratios are plotted against the material coordinate, z , for ease in comparing past, present, and future distributions. The conventional layer height, ξ coordinate, equivalent to z can be found in the problem listing in Appendix C.

72. The distribution of excess pore pressure within the dredged fill at the end of the second year and before the next layer is deposited is shown in Figure 23 along with the distribution at year 1 after

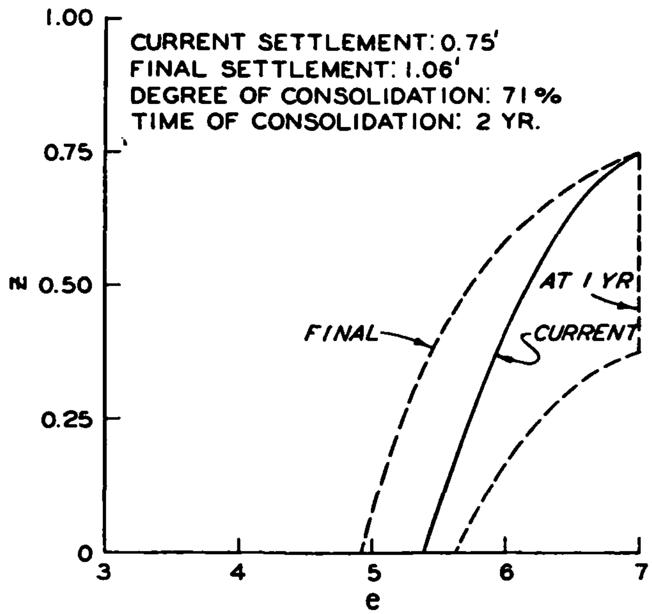

Figure 22. Void ratio distribution at the end of year 2

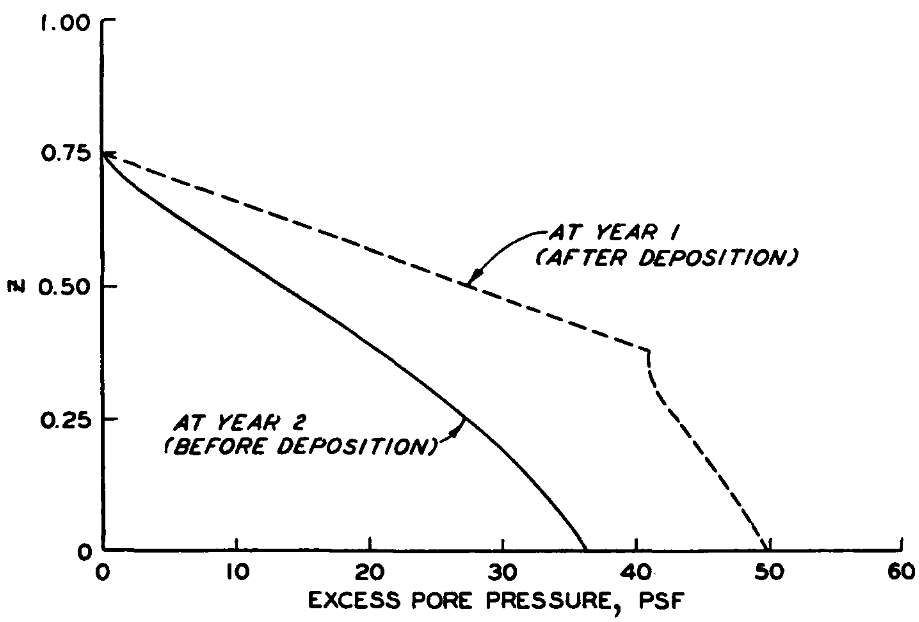

Figure 23. Excess pore pressure distribution at the end of year 2

deposition of the second layer. The discontinuity in the year 1 curve is due to the assumption that the second layer is deposited instantaneously and its excess pore pressure is superimposed on the existing excess pressure before the layer was deposited. At the end of consolidation there is no excess pore pressure, and thus a final curve is not shown. Curves of this type are useful in evaluating strength or stability using an effective stress analysis. Distributions of total and effective stresses can be found in tabular form in the problem listing in Appendix C.

73. Figure 24 depicts void ratio distributions throughout the dredged fill deposition period and the final distribution for the total amount of material deposited. This figure shows that even after 100 percent primary consolidation, very high void ratios will exist throughout the dredged fill material and unless some later load causing further consolidation is placed, the material may never be suitable for any engineering purpose. The effects of surface desiccation and secondary consolidation are not considered here, even though these factors will have an impact on the final void ratio distribution. The effects of these factors will be considered in future extensions of the theoretical basis and computer program.

74. Shown in Figure 25 are excess pore pressure distributions in the later years of consolidation. Again, this type of figure would be useful in evaluating strength or stability using an effective stress analysis. Tabulations for year 14 can also be found in Appendix C.

75. Figures 26 and 27 are plots of the degrees of consolidation and settlement, respectively, throughout the period of deposition and for 9 years after deposition ceases. Also shown in the figures are the results of a conventional or small strain analysis of the same disposal program estimated from consolidation charts (Terzaghi and Peck 1967, Lambe and Whitman 1969). The difference between the two theoretical approaches is clearly evident. The sudden drops in the degree of consolidation at years 1 through 7 are due to the instant application of additional dredged fill at those times. As can be seen, 90 percent consolidation is achieved at about 12.8 years by finite strain theory; whereas, the deposit is only about 55 percent consolidated at this time

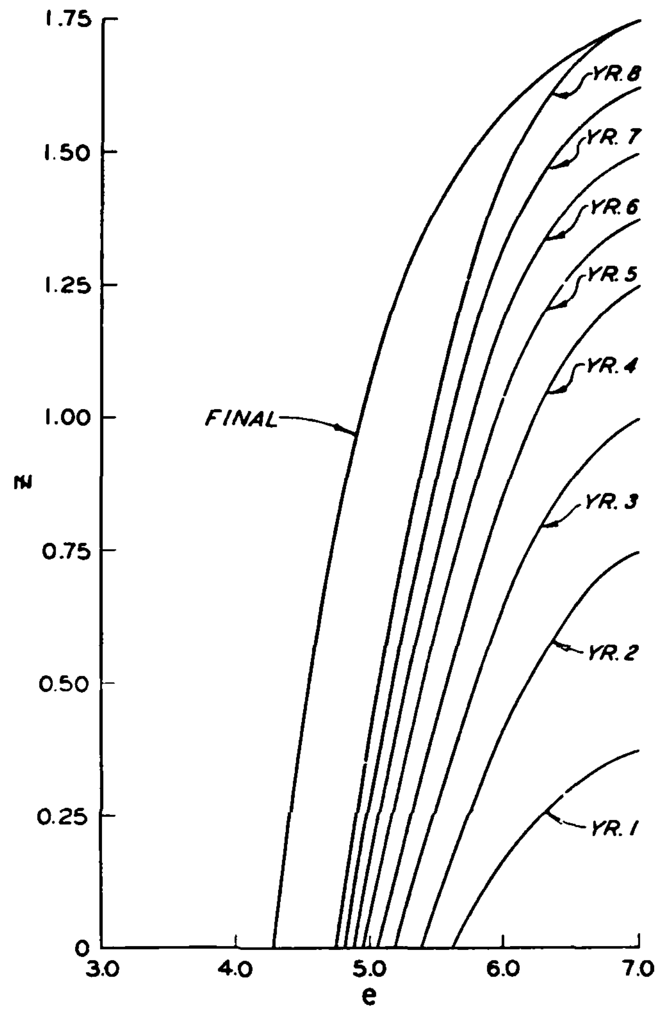

Figure 24. Void ratio distributions at the end of each year during deposition and ultimately

by small strain theory. The predicted ultimate settlement is essentially the same in both calculations since the original individual layer heights were relatively small. It should be noted that the small strain analysis was a hand calculation and more elaborate computer applications of the theory may reduce somewhat the differences shown, but results from the use of the two theories will never match due to the basic differences in the theories.

76. For containment area design purposes, the results of the

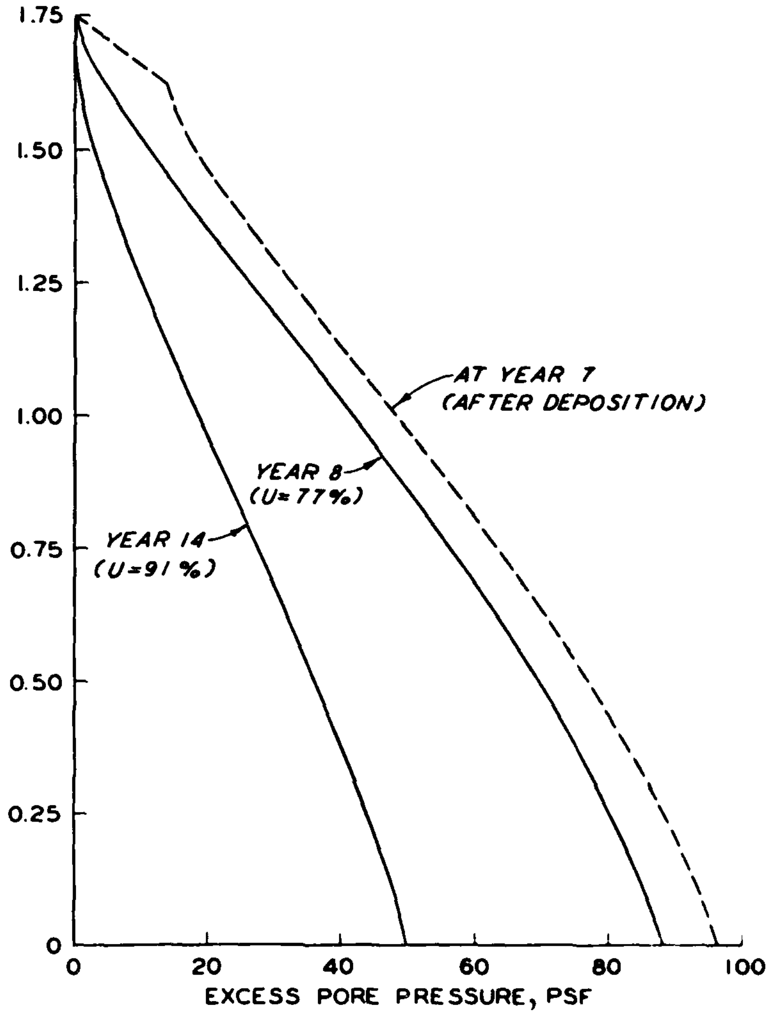

Figure 25. Excess pore pressure distribution at years 7, 8, and 14

finite strain analysis of the dredged fill and compressible foundation can be plotted as shown in Figure 28. With this representation of the dredged fill surface and foundation surface, the height of containment area dikes required during the period of disposal can be readily determined.

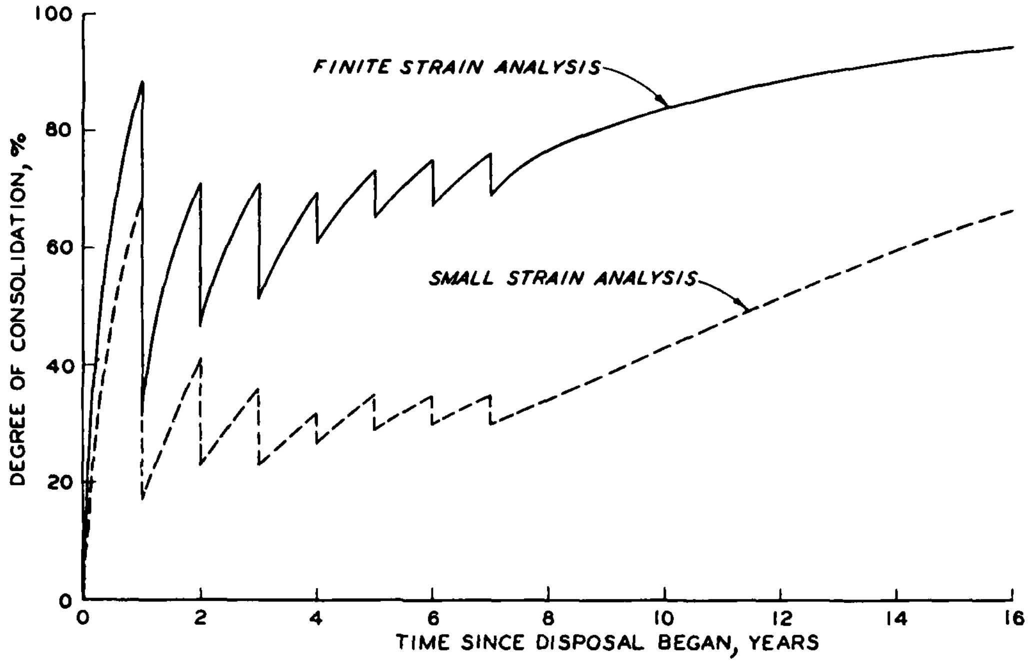

Figure 26. Degree of consolidation by finite strain analysis compared to a small strain analysis

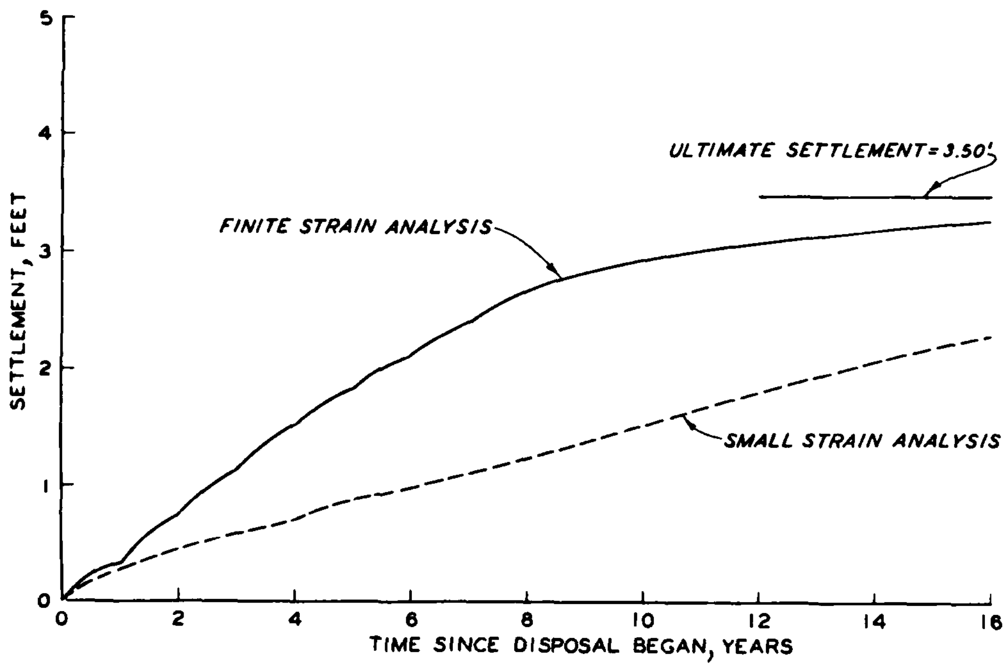

Figure 27. Settlements by finite strain analysis compared to a small strain analysis

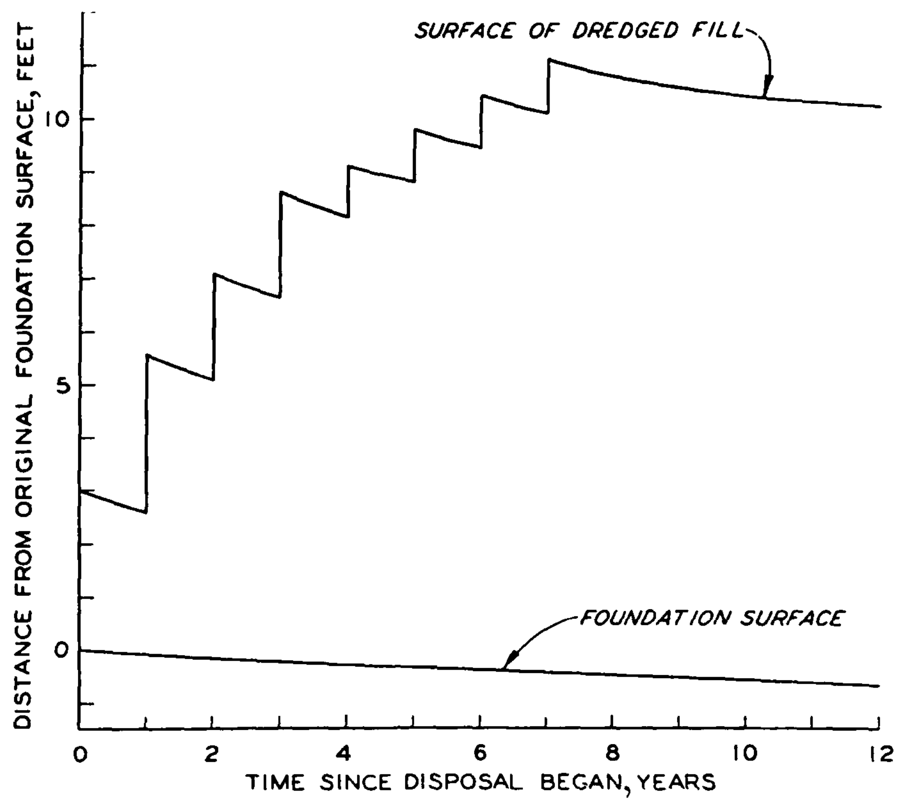

Figure 28. Heights of the dredged fill and foundation surfaces during and after disposal operations

Consolidation of a Soft Thick Layer

77. This example will illustrate the program's capability to calculate primary consolidation in a soft thick layer which is normally consolidated under a small overburden when subjected to a series of added surcharges. The layer is assumed to be 20 ft thick and to overlie a coarse sand so that its lower boundary may be considered free draining. The layer's void ratio-effective stress and void ratio-permeability relationships are those shown in Figures 16 and 20, and the layer's specific gravity of solids was assumed to be 2.80.

78. It is further assumed that initially the top of the layer is about 1 ft below the water table and some years ago was covered with 1 ft of sandy material so that it is fully consolidated under about 75 psf of

overburden. It is planned to hydraulically fill the area with an additional 10 ft of sand over the next three years to prepare it for construction of light buildings. The sand will be dredged from nearby sources and deposited according to the schedule shown in Figure 29, which also depicts initial layer conditions. It is required to determine consolidation behavior of the compressible layer during and subsequent to surcharge additions.

79. Based on program calculations, void ratio distributions can be plotted for any time during the consolidation process. Figure 30 shows such distributions for the first three years of the example in comparison to the initial and final void ratios in the layer. The distributions at years 1 and 2 are before the surcharges for those years are added. As can be seen from the figure, wide variation in void ratios occurs throughout the layer initially and until it is finally consolidated under the total added surcharge. Thus again, the inapplicability of a small strain analysis which assumes a constant distribution of void ratios is manifest.

80. The distribution of excess pore pressures at various times during consolidation is shown in Figure 31. The principal information

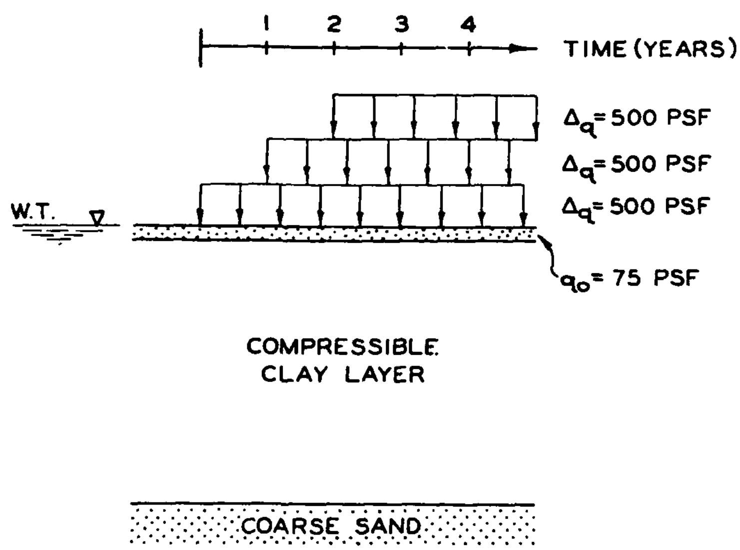

Figure 29. Schedule of surcharges added to compressible clay layer

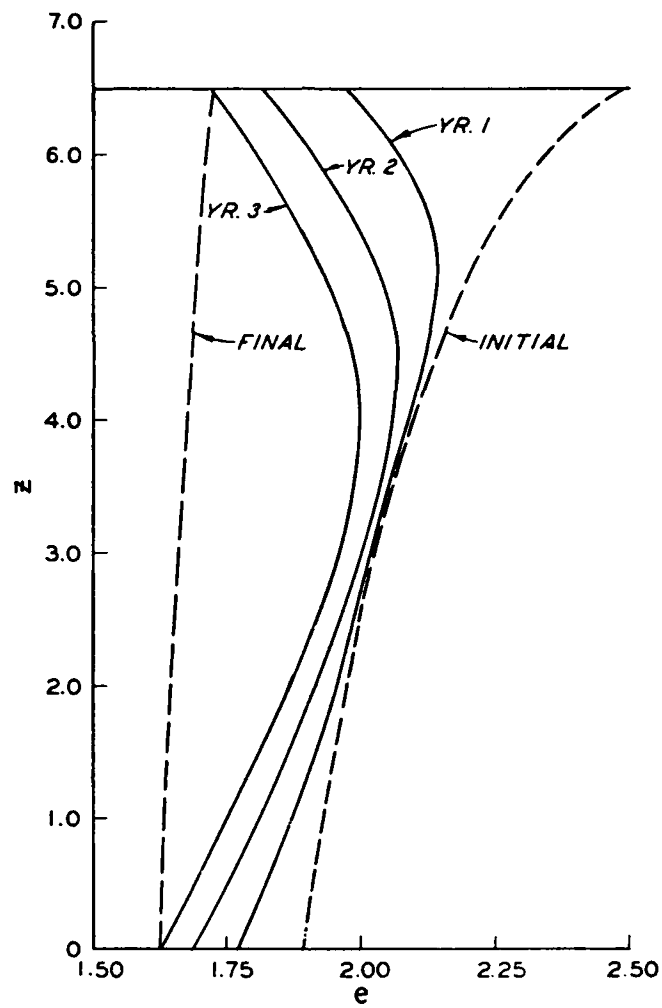

Figure 30. Void ratio distributions
in the compressible layer

to be gained from this figure is the fallacy of the often-made assumption that the value of the remaining excess pore pressure is its maximum amount reduced by a percentage equal to the degree of consolidation. For instance, at 57 percent consolidation the remaining excess pore pressure is more than 89 percent of its maximum value, at 76 percent consolidation it is 58 percent, and at 91 percent consolidation, it is about 25 percent of the original maximum value.

81. Figures 32 and 33 compare the degree of consolidation and settlements respectively as predicted by the finite strain analysis

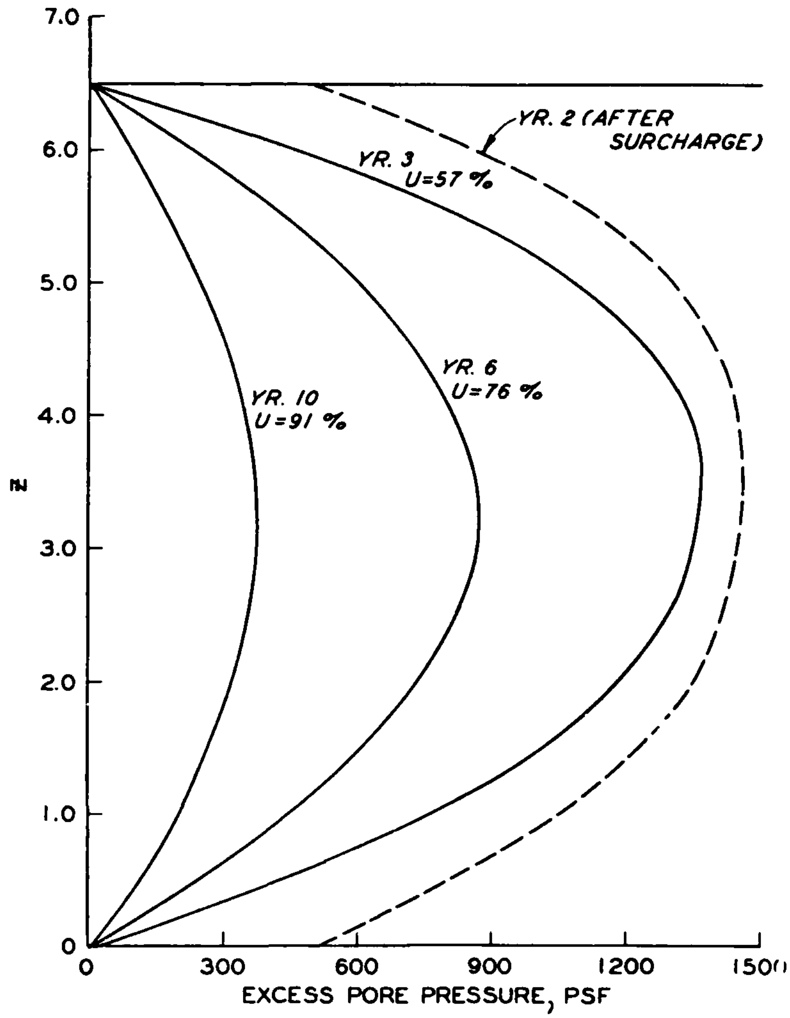

Figure 31. Excess pore pressure distribution in the compressible layer

and a small strain analysis. Once again the difference in the two theoretical approaches is clearly evident, and as in the dredged fill example, consolidation is predicted to occur at a faster rate by the finite strain analysis. Even though consolidation occurs faster, the dissipation of excess pore pressure is predicted to occur slower. Figure 34 shows the excess pore pressure distribution by both theories at year 6 during consolidation. This figure shows that the small strain theory is underconservative when used to predict pore pressures and therefore may lead to underconservative safety factors when used in stability analyses.

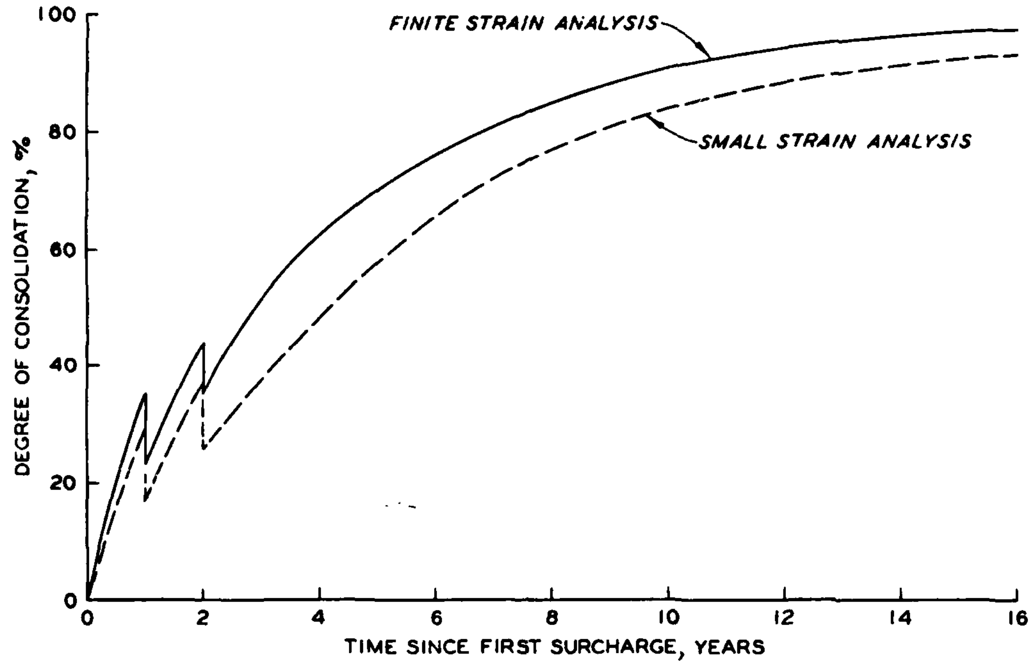

Figure 32. Degree of consolidation comparison between finite strain and small strain analyses for a compressible layer

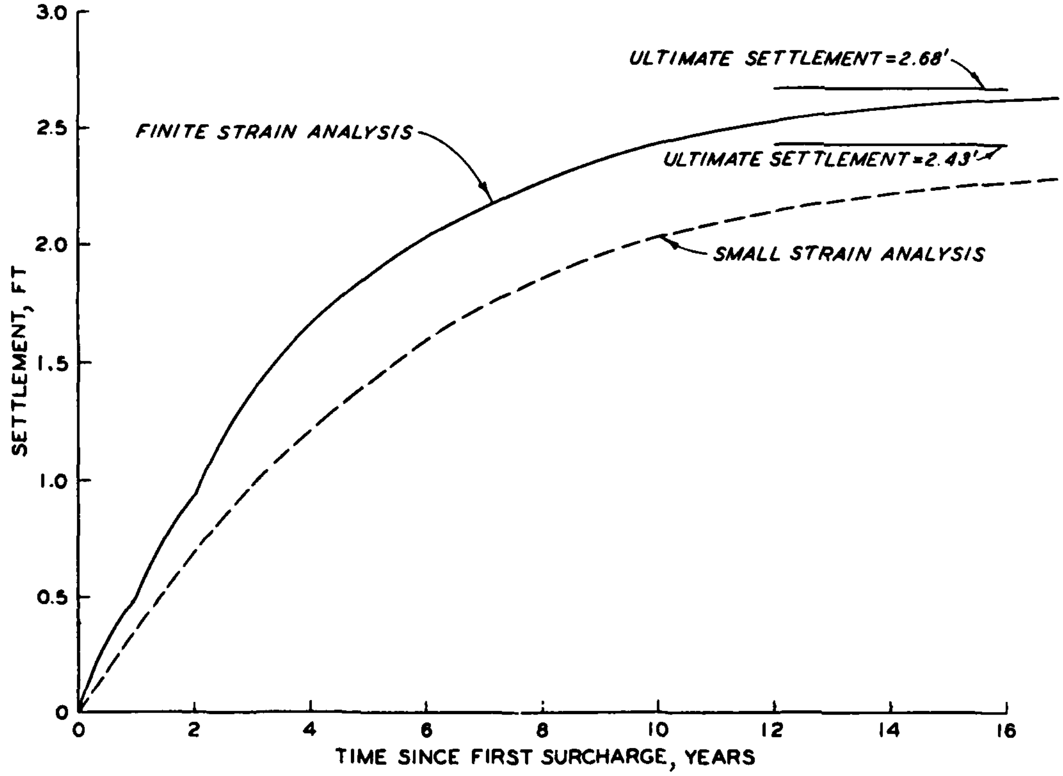

Figure 33. Predicted settlement comparison between finite strain and small strain analyses for a compressible layer

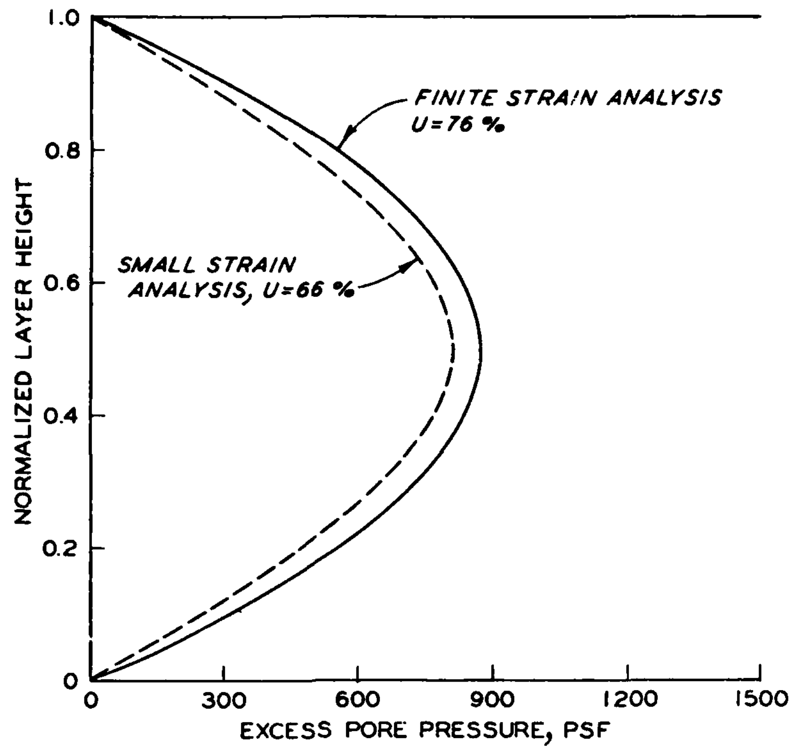

Figure 34. Excess pore pressure distribution at year 6 in the compressible layer as predicted by finite strain and small strain analyses

82. A listing of problem input and calculations to years 3 and 6 are included in Appendix C. The calculation constants τ and δ were 1.0 day and one-tenth of the layer height, respectively. These selections proved to be sufficient for stability and provided for an economic calculation.

PART VI: SUMMARY

83. This report has developed the theory of finite strain consolidation in relatively simple and concise terms and shown how the theory can be effectively programmed for computer computation of the consolidation behavior of very soft single or multiple layers of fine grained materials. In the theory development, simplifying assumptions have been held to a minimum which effectively makes the theory the most general in defining one-dimensional consolidation. The chief advantages of finite strain theory over small strain theory are its independence from strain levels, its independence of any set relationship between void ratio and effective stress, and its consideration of the variabilities in permeability through the consolidating layer due to changes in void ratio.

84. The computer program, CSLFS, documented in this report represents an alternative to the conventional methods of calculating one-dimensional consolidation which was previously unavailable. The program was purposely written to require only the most basic soil property data, i.e., point data from laboratory testing relating effective stress and permeability to the void ratio. It also provides for the very real case of a semipermeable boundary. Although the program was intentionally structured to facilitate the calculation of consolidation in multiple dredged fill layers deposited on a compressible foundation, it is equally suitable for making one-dimensional consolidation predictions in a clay layer subjected to more traditional foundation type loads.

85. As shown by the example problems worked in the report, this method of consolidation prediction is not merely a more detailed analysis which leads to essentially the same results obtained through a simpler small strain analysis. There is a real and substantial difference in the results and indications are that the finite strain method is more accurate because of consistent underprediction of settlements in designs using small strain theories. Therefore, the program should prove to be a valuable aid in future designs requiring a prediction of one-dimensional consolidation as a function of time.

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APPENDIX A: USER'S MANUAL FOR CSLFS

1. This appendix will provide information useful to users of the computer program CSLFS to include a general description of the program processing sequence, definitions of principal variables, and format requirements for problem input. The program was originally written for use on the WES Time-sharing System but could be readily adapted to batch processing through a card reader and high-speed line printer. Some output format changes would be desirable if the program were used in batch processing to improve efficiency.

2. The program is written in FORTRAN IV computer language with eight-digit line numbers. However, characters 9 through 80 are formatted to conform to the standard FORTRAN statement when reproduced in spaces 1 through 72 of a computer card. Program input is through a quick access type file previously built by the user. Output is either to the time-sharing terminal or to a file which must be saved by the user at the end of a run. Program options will be fully described in the remainder of this appendix.

3. A listing of the program is provided in Appendix B, and typical solution output is contained in Appendix C.

Program Description and Components

4. CSLFS is composed of the main program and ten subroutines. It is broken down into subprograms to make modification and understanding easier. The program is also well documented throughout with comments, so a detailed description will not be given. However, an overview of the program structure is shown in Figure A1, and a brief statement about each part follows:

Main Program. In this part, input data are read according to the option specified and the various subroutines are called to print initial data, calculate consolidation and stresses, and print solution output.

Subroutine INTRO. This subprogram causes a heading to be printed, prints soil and calculation data, and

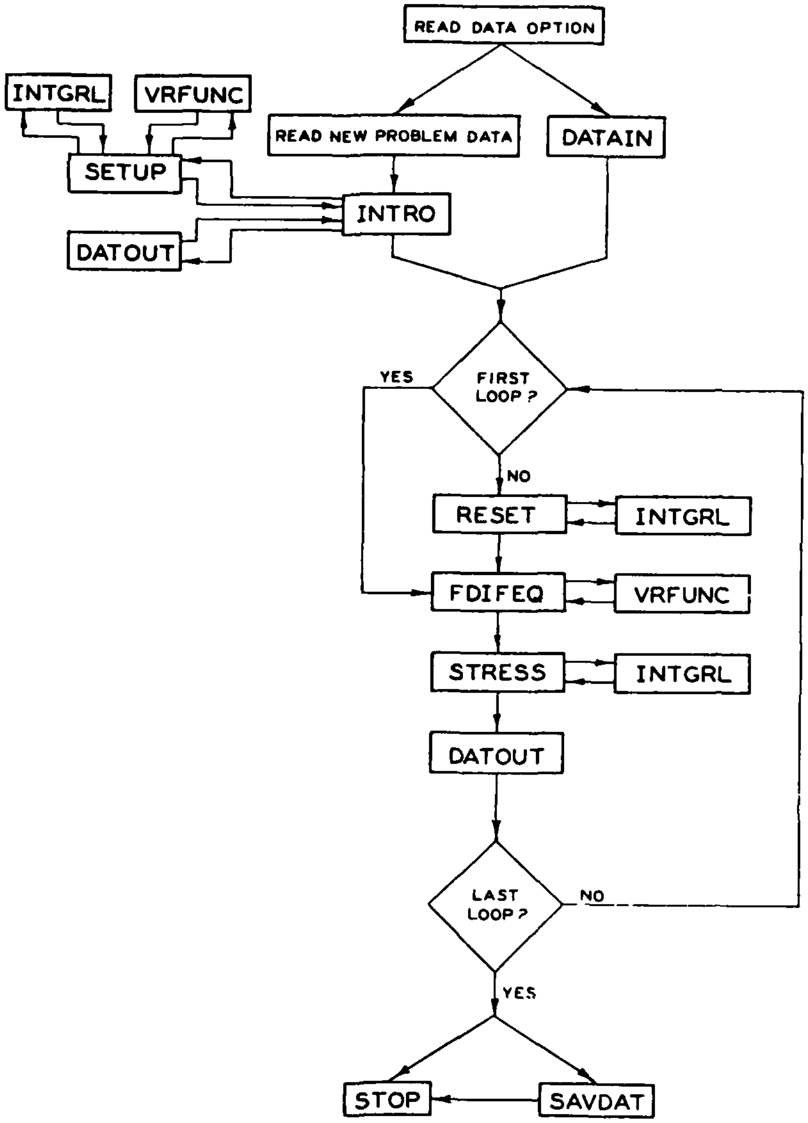

Figure A1. Flow diagram of computer program CSLFS

prints initial conditions in each initial consolidating layer.

Subroutine SETUP. SETUP calculates the initial and final void ratios, coordinates, stresses, and final settlements in each initial consolidating layer. It also calculates the various void ratio functions:

$$\frac{k}{1 + e} , \quad \frac{d\sigma'}{de} , \quad \alpha(e) , \text{ and } \quad \beta(e)$$

from input relationships between void ratio, effective stress, and permeability.

Subroutine RESET. In this subroutine initial conditions are modified each time a new dredged fill layer or surcharge is added to the consolidating layers. The subprogram also calculates new final settlements and resets the bottom boundary pressure gradient.

Subroutine FDIFEQ. This is where consolidation is actually calculated. A finite difference equation is solved for each nodal point in the consolidating layers at each time step between specified output times. Void ratio functions and pore pressure gradients at layer boundaries are also recalculated at each time step. Just before each output time, consistency and stability criteria are checked.

Subroutine VRFUNC. The functions $\alpha(e)$ and $\beta(e)$ required at each time step in FDIFEQ are calculated in this subprogram.

Subroutine STRESS. Here, the current convective coordinates, soil stresses, and pore pressures are calculated for each output time.

Subroutine INTGRL. This subroutine evaluates the void ratio integral used in determining convective coordinates, settlements, and soil stresses. The procedure is by Simpson's rule for odd or even numbered meshes.

Subroutine DATOUT. DATOUT prints the results of consolidation calculations and initial conditions in tabular form. Examples are shown in Appendix C.

Subroutine DATAIN. This subprogram reads the data from a previous program run so that future consolidation can be calculated without having to recalculate previous consolidation.

Subroutine SAVDAT. The data from the current program run is written to a file in the format required to be read by DATAIN.

Variables

5. The following is a list of the principal variables and variable arrays that are used in the computer program CSLFS. The meaning of each variable is also given along with other pertinent information about

it. If the variable name is followed by a number in parentheses, it is an array, and the number denotes the current array dimensions. If these dimensions are not sufficient for the problem to be run, they must be increased throughout the program.

A(101)	the Lagrangian coordinate of each space mesh point in the dredged fill layers.
A1(11)	the Lagrangian coordinate of each space mesh in the compressible foundation or layer.
AF(101)	the function $\alpha(e)$ corresponding to the current void ratios at each space mesh point in the dredged fill layers.
AF1(11)	the function $\alpha(e)$ corresponding to the current void ratios at each space mesh point in the compressible foundation or layer.
AHDF(10)	the initial height of added dredged fill layers in Lagrangian coordinates or the amount of added surcharge on a compressible layer.
ALPHA(51)	the function $\alpha(e)$ corresponding to the void ratios input when describing the void ratio-effective stress and permeability relationships for the dredged fill.
ALPHA1(51)	the function $\alpha(e)$ as above except for the compressible foundation or layer.
BETA(51)	the function $\beta(e)$ corresponding to the void ratios input when describing the void ratio-effective stress and permeability relationships for the dredged fill.
BETA1(51)	the function $\beta(e)$ as above except for the compressible foundation or layer.
BF(101)	the function $\beta(e)$ corresponding to the current void ratios at each space mesh point in the dredged fill layers.
BF1(11)	the function $\beta(e)$ corresponding to the current void ratios at each space mesh point in the compressible foundation or layer.
DA	the difference between the Lagrangian coordinates of space mesh points in the dredged fill layer.
DSDE(51)	the calculated value of $\frac{d\sigma'}{de}$ corresponding to the void ratios input when describing the void ratio-effective stress relationship for the dredged fill.

DSDE1(51)	the calculated value of $\frac{d\sigma'}{de}$ as above except for the compressible foundation or layer.
DUØ	the drainage path length in an incompressible boundary layer used for computing the semi-permeable boundary condition. This value is originally input in Lagrangian coordinates but is changed to material coordinates by the program.
DUDZ1Ø	the excess pore pressure gradient in an incompressible foundation at its boundary with the compressible layer.
DUDZ11	the excess pore pressure gradient in the compressible foundation or layer at its boundary with an incompressible foundation.
DUDZ21	the excess pore pressure gradient in the dredged fill layer at its boundary with a compressible foundation or incompressible foundation.
DZ	the difference between the material or reduced coordinates of space mesh points in the dredged fill.
DZ1	the difference between the material or reduced coordinates of space mesh points in the compressible foundation or layer.
DQ	the initial additional surcharge placed on a compressible layer.
E(101)	the current void ratios at each space mesh point in the dredged fill.
EØ	the void ratio in the incompressible foundation at its boundary with the compressible layer.
EØØ	the initial void ratio assumed by the dredged fill after initial sedimentation and before consolidation.
E1(101)	the initial void ratios at each space mesh point in the dredged fill.
E11(11)	the initial void ratios at each space mesh point in the compressible foundation or layer.
EFFSTR(101)	the effective stress at each space mesh point in the dredged fill.
EFIN(101)	the final (100 percent primary consolidation) void ratios at each space mesh point in the dredged fill.
EFIN1(11)	the final (100 percent primary consolidation)

void ratios at each space mesh point in the compressible foundation or layer.

EFSTR1(11)	the effective stress at each space mesh point in the compressible foundation or layer.
ELL	the total depth of the dredged fill in material or reduced coordinates.
ELL1	the depth of the compressible foundation or layer in material or reduced coordinates.
ER(11)	the current void ratios at each space mesh point in the compressible foundation or layer.
ES(51)	the void ratios input when describing the void ratio-effective stress and permeability relationships in the dredged fill.
ES1(51)	the void ratios input when describing the void ratio-effective stress and permeability relationships in the compressible foundation or layer.
F(101)	the void ratios at each space mesh point of the previous time step in the dredged fill.
F1(11)	the void ratios at each space mesh point of the previous time step in the compressible foundation or layer.
FINT(101)	the void ratio integrals evaluated from the bottom to the subscripted space mesh point in the dredged fill.
FINT1(11)	the void ratio integrals evaluated from the bottom to the subscripted space mesh point in the compressible foundation or layer.
GC	the buoyant unit weight of the dredged fill soil solids.
GC1	the buoyant unit weight of the soil solids of the compressible foundation or layer.
GS	the unit weight of the dredged fill soil solids.
GS1	the unit weight of the soil solids of the compressible foundation or layer.
GSBL	the specific gravity of the soil solids of the compressible foundation or layer.
GSDF	the specific gravity of the dredged fill soil solids.
GW	the unit weight of water.
HBL	the initial height of the compressible foundation or layer in Lagrangian coordinates.

HDF	the initial height of the first dredged fill layer in Lagrangian coordinates.
HDF1	the initial height of later dredged fill layers in Lagrangian coordinates.
IN	an integer denoting the input mode or device for initial problem data which has the value "10" in the present program.
INS	an integer denoting the input mode or device for problem data from a previous computer run which has the value "12" in the present program.
IOUT	an integer denoting the output mode or device for recording the results of program computations in a user's format which has the value "11" in the present program.
IOUTS	an integer denoting the output mode or device for recording the results of program computations in a format for continuing the computations in a later run which has the value "13" in the present program.
LBL	the number of data points used in describing the void ratio-effective stress and permeability relationships in the compressible foundation or layer.
LDF	the number of data points as above except for the dredged fill.
MTIME	the number of additional output times when continuing a previous computer run.
NBDIV	the number of parts the initial dredged fill layer is divided into for computation purposes.
NBDIV1	the number of parts the compressible foundation or layer is divided into for computation purposes.
NBL	an integer denoting the following options: 1 = consolidation calculated for dredged fill layers and a compressible foundation. 2 = consolidation calculated for dredged fill layers only. 3 = consolidation calculated for a single compressible layer only.
ND	the total number of space mesh points in the dredged fill layers.

NDATA1 — an integer denoting the following options:

1 = this is a new problem and data will be read from file "10".

2 = this is a continuation of a previous computer run and data will be read from file "12".

NDATA2 — an integer denoting the following options:

1 = do not save data for later computer run.

2 = save data on file "13" so that calculations can be continued in a later computer run.

NDIV — the number of space mesh points in the initial dredged fill layer.

NDIV1 — the total number of space mesh points in the compressible foundation or layer.

NFLAG — an integer denoting the following:

0 = print current conditions heading.

1 = print initial conditions heading.

NM — an integer counter which is used in tracking the output times for each computer run.

NND — an integer used to denote the total number of parts into which the dredged fill layers are divided for computation purposes.

NNN — an integer counter which is used in tracking the total number of time steps through which consolidation has proceeded.

NPROB — an integer used as a label for the current consolidation problem.

NPT — an integer denoting the following options:

1 = make a complete computer run, printing soil data, initial cnditions, and current conditions for all specified print times.

2 = make a complete computer run but do not print soil data and initial conditions.

3 = terminate computer run after printing soil data and initial conditions.

NST — an integer line number used on each line of data input and on data lines output for use in a later computer run.

NTIME	the number of output times during the initial computer run of a consolidation problem.
PK(51)	the function $\frac{k}{1 + e}$ corresponding to the void ratios input when describing the void ratio-permeability relationship in the dredged fill.
PKØ	the function $\frac{k}{1 + e}$ for the incompressible foundation layer.
PK1(51)	the function $\frac{k}{1 + e}$ corresponding to the void ratios input when describing the void ratio-permeability relationship in the compressible foundation or layer.
PRINT(25)	the real times at which current conditions in the consolidating layers will be output.
QØ	the initial overburden on a compressible layer.
Q1	the current total surcharge including overburden on a compressible layer.
RK(51)	the permeabilities input when describing the void ratio-permeability relationship in the dredged fill.
RK1(51)	the permeabilities input as above except for the compressible foundation or layer.
RS(51)	the effective stresses input when describing the void ratio-effective stress relationship in the dredged fill.
RS1(51)	the effective stresses input as above except for the compressible foundation or layer.
RWL(10)	the new height of free water surface above the bottom of the compressible foundation or layer after a new dredged fill layer or surcharge has been added.
SETT	the current settlement in the dredged fill.
SETT1	the current settlement in the compressible foundation or layer.
SFIN	the final settlement in the dredged fill layer presently existing.
SFIN1	the final settlement in the compressible foundation or layer under present loading conditions.
TAU	the value of the time step in the finite difference calculations.

TIME	the real time value after each time step.
TPRINT	the real time value of the next output point.
TOSTR1(11)	the current total stress at each space mesh point in the compressible foundation or layer.
TOTSTR(101)	the current total stress at each space mesh point in the dredged fill.
U(101)	the current excess pore pressure at each space mesh point in the dredged fill.
UØ(101)	the current static pore pressure at each space mesh point in the dredged fill.
UØ1(11)	the current static pore pressure at each space mesh point in the compressible foundation or layer.
U1(11)	the current excess pore pressure at each space mesh point in the compressible foundation or layer.
UCON	the current degree of consolidation in the dredged fill.
UCON1	the current degree of consolidation in the compressible foundation or layer.
UW(101)	the current total pore pressure at each space mesh point in the dredged fill.
UW1(11)	the current total pore pressure at each space mesh point in the compressible foundation or layer.
VRI1	the initial total void ratio integral for the compressible foundation or layer.
WL	the initial height of free water surface above the bottom of the first dredged fill layer.
WL1	the initial height of free water surface above the bottom of the compressible foundation or layer.
XI(101)	the current convective coordinate of each space mesh point in the dredged fill.
XI1(11)	the current convective coordinate of each space mesh point in the compressible foundation or layer.
Z(101)	the material or reduced coordinate of each space mesh point in the dredged fill.
Z1(11)	the material or reduced coordinate of each space mesh point in the compressible foundation or layer.

ZKØ the permeability in the incompressible foundation at its boundary with the compressible layer.

Problem Data Input

6. The method of inputting problem data in CSLFS is by a free field data file containing line numbers. The line number must be eight characters or less for ease in file editing and must be followed by a blank space. The remaining items of data on each line must be separated by a comma or blank space. Real data may be either written in exponential or fixed decimal formats, but integer data must be written without a decimal.

7. For an initial problem run (i.e., NDATA1 = 1), the data file should be sequenced in the following manner:

- a. NST, NPROB, NDATA1, NDATA2
- b. NST, NPT, NBL
- c. NST, GSBL, HBL, WL1, LBL, QØ, DQ
- d. NST, ES1(I), RS1(I), RK1(I)
- e. NST, GSDF, HDF, WL, LDF, EØØ, GW
- f. NST, ES(I), RS(I), RK(I)
- g. NST, EØ, ZKØ, DUØ
- h. NST, NBDIV, NBDIV1, TAU, NTIME
- i. NST, PRINT(I), AHDF(I), RWL(I)

It should be pointed out here that NST may be any positive integer but must increase throughout the file so that it will be read in the correct sequence in the time-sharing system.

8. The following exceptions and explanations should also be noted for particular line types:

Line type c: QØ and DQ have nonzero values only if NBL = 3. If NBL = 2, all data values are set to zero except NST.

Line type d: There are LBL of these lines unless NBL = 2, and then there will be one line with all values set to zero except NST.

Line type e: If NBL = 3, all values on this line are set to zero except NST and GW.

Line type f: Ther are LDF of these lines unless NBL = 3, and then there will be one line with all values set to zero except NST.

Line type i: There are NTIME of these lines.

9. For the continuation of a previous problem run (i.e., NDATA1 = 2), the input data file should be input in the following sequence:

Line type aa. NST, NPROB, NDATA1, NDATA2

Line type bb. NST, MTIME

Line type cc. NST, AHDF(NTIME), RWL(NTIME)

Line type dd. NST, PRINT(I), AHDF(I), RWL(I)

10. The following explanations should be noted for particular line types:

Line type cc: AHDF and RWL are the values from the last line of the previous computer run.

Line type dd: There are MTIME of the lines.

11. All input data having particular units must be consistent with all other data. For example, if layer thickness is in feet and time is in days, then permeability must be in feet per day. If stresses are in pounds per square foot, then unit weights must be in pounds per cubic foot. Any system of units is permissible so long as consistency is maintained.

APPENDIX B: CSLFS PROGRAM LISTING

1. The following is a complete listing of CSLFS as written for the WES time-sharing system.

```
CCSLFS  CONSOLIDATION OF SOFT LAYERS BY FINITE STRAIN
C
C
C       ****************************************************
C       *                                                  *
C       *                     CSLFS                        *
C       *                                                  *
C       * ONE-DIMENSIONAL FINITE STRAIN CONSOLIDATION      *
C       *                                                  *
C       *                       OF                         *
C       *                                                  *
C       *          HOMOGENEOUS SOFT CLAY LAYERS            *
C       *                                                  *
C       ****************************************************
C
C
C    *********************************************************
C    *                                                       *
C    * CSLFS COMPUTES THE VOID RATIOS, TOTAL AND EFFECTIVE   *
C    * STRESSES, PORE WATER PRESSURES, SETTLEMENTS, AND      *
C    * DEGREES OF CONSOLIDATION FOR HOMOGENEOUS SOFT CLAY    *
C    * LAYERS OF DREDGED FILL DEPOSITED ON A COMPRESSIBLE    *
C    * OR INCOMPRESSIBLE LAYER BY FINITE STRAIN CONSOLIDATION
C    * THEORY.  LOWER BOUNDARY OF THE BOTTOM COMPRESSIBLE    *
C    * LAYER MAY BE COMPLETELY FREE DRAINING, IMPERMEABLE,   *
C    * OR NEITHER.  THE VOID RATIO-EFFECTIVE STRESS AND      *
C    * VOID RATIO-PERMEABILITY RELATIONSHIPS ARE INPUT AS    *
C    * POINT VALUES AND THUS MAY ASSUME ANY FORM.            *
C    *                                                       *
C    *********************************************************
C
C
      COMMON   DA,DU0,DUDZ10,DUDZ11,DUDZ21,DZ,DZ1,D0,E0,E00,ELL,ELL1,
     &         GC,GC1,GS,GS1,GSBL,GSDF,GW,HBL,HDF,HDF1,IN,INS,IOUT,
     &         IOUTS,LBL,LDF,MTIME,NBDIV,NBDIV1,NBL,ND,NDIV,NDIV1,
     &         NFLAG,NM,NPROB,NPT,NND,NNN,NTIME,PK0,Q0,Q1,SETT,SETT1,
     &         SFIN,SFIN1,TAU,TIME,TPRINT,UCON,UCON1,VRI1,WL,WL1,ZK0,
     &         A(101),A1(11),AF(101),AF1(11),ALPHA(51),ALPHA1(51),
     &         BETA(51),BETA1(51),BF(101),BF1(11),DSDE(51),DSDE1(51),
     &         E(101),E1(101),E11(11),EFIN(101),EFIN1(11),EP(11),
     &         ES(51),ES1(51),EFFSTR(101),EFSTR1(11),F(101),F1(11),
     &         FINT(101),FINT1(11),PK(51),PK1(51),RK(51),RK1(51),
     &         RS(51),RS1(51),TOTSTR(101),TOSTR1(11),U(101),U1(11),
     &         U0(101),U01(11),UW(101),UW1(11),XI(101),XI1(11),
     &         Z(101),Z1(11)
      DIMENSION   AHDF(10),PRINT(25),RWL(10)
C
```

```
C
C      ...SET INPUT AND OUTPUT MODES
       IN = 10
       IOUT = 11
       INS = 12
       IOUTS = 13
C      ...READ PROBLEM INPUT FROM FREE FIELD DATA FILE
C      .....CONTAINING LINE NUMBERS
   100 FORMAT(V)
C      .....PROBLEM NUMBER, DATA OPTIONS, INTRO OPTION, FDT OPTION
       READ(IN,100) NST,NPROB,NDATA1,NDATA2
       IF (NDATA1 .EQ. 2) GOTO 4
       READ(IN,100) NST,NPT,NBL
C      .....SOIL DATA FOR FOUNDATION LAYER OR SOFT LAYER
       READ(IN,100) NST,GSBL,HBL,WL1,LBL,O0,D0
       DO 1  I=1,LBL
       READ(IN,100) NST,ES1(I),RS1(I),RK1(I)
     1 CONTINUE
C      .....SOIL DATA FOR DREDGED FILL
       READ(IN,100) NST,GSDF,HDF,WL,LDF,E00,GW
       DO 2  I=1,LDF
       READ(IN,100) NST,ES(I),RS(I),RK(I)
     2 CONTINUE
C      .....CONSOLIDATION CALCULATION DATA
       READ(IN,100) NST,E0,ZK0,DU0
       READ(IN,100) NST,NBDIV,NBDIV1,TAU,NTIME
       DO 3  I=1,NTIME
       READ(IN,100) NST,PRINT(I),AHDF(I),RWL(I)
     3 CONTINUE
C
C      ...SET INITIAL VARIABLES
       ELL1 = 0.0 ; DZ1 = 0.0
       TIME = 0.0
       UCON = 0.0 ; UCON1 = 0.0
       SETT = 0.0 ; SETT1 = 0.0
       SFIN = 0.0 ; SFIN1 = 0.0 ; VRI1 = 0.0
       NNN = 1 ; NM = 1
       DA = 0.0 ; DZ = 1.0 ; HDF1 = 0.0
       DUDZ11 = 0.0 ; DUDZ2T = 0.0
       O1 = O0 + D0
C
```

```
C     ...PRINT INPUT DATA AND MAKE INITIAL CALCULATIONS
      CALL INTRO
      IF (NPT .EQ. 3) STOP
      GOTO 6
C
C     ...NEW CONSOLIDATION TIMES AND DATA
    4 READ(IN,100) NST,MTIME
      CALL DATAIN
      READ(IN,100) NST,AHDF(NM-1),PWL(NM-1)
      DO 5  I=NM,NTIME
      READ(IN,100) NST,PRINT(I),AHDF(I),PWL(I)
    5 CONTINUE
C
C     ...PERFORM CALCULATIONS TO EACH PRINT TIME AND OUTPUT RESULTS
    6 DO 8  K=NM,NTIME
      TPRINT = PRINT(K)
      IF (K .EQ. 1) GOTO 7
      HDF1 = AHDF(K-1)
      WL1 = PWL(K-1)
      CALL RESET
    7 CALL FDIFEQ
      CALL STRESS
      CALL DATOUT
    8 CONTINUE
C
      IF (NDATA2 .EQ. 2)  CALL SAVDAT
C
      STOP
      END
C
C
```

```
      SUBROUTINE INTRO
C
C     **********************************************
C     * INTRO PRINTS INPUT DATA AND RESULTS OF INITIAL *
C     * CALCULATIONS IN TABULAR FORM.                  *
C     **********************************************
C
      COMMON  DA,DU0,DUDZ10,DUDZ11,DUDZ21,DZ,DZ1,D0,E0,E00,ELL,ELL1,
     &        GC,GC1,GS,GS1,GSBL,GSDF,GW,HBL,HDF,HDF1,IN,INS,IOUT,
     &        IOUTS,LBL,LDF,MTIME,NBDIV,NBDIV1,NBL,ND,NDIV,NDIV1,
     &        NFLAG,NM,NPROB,NPT,NND,NNN,NTIME,PK0,Q0,Q1,SETT,SETT1,
     &        SFIN,SFIN1,TAU,TIME,TPRINT,UCON,UCON1,VRI1,WL,WL1,ZK0,
     &        A(101),A1(11),AF(101),AF1(11),ALPHA(51),ALPHA1(51),
     &        BETA(51),BETA1(51),BF(101),BF1(11),DSDE(51),DSDE1(51),
     &        E(101),E1(101),E11(11),EFIN(101),EFIN1(11),ER(11),
     &        ES(51),ES1(51),EFFSTR(101),EFSTR1(11),F(101),F1(11),
     &        FINT(101),FINT1(11),PK(51),PK1(51),RK(51),RK1(51),
     &        RS(51),RS1(51),TOTSTR(101),TOSTR1(11),U(101),U1(11),
     &        U0(101),U01(11),UW(101),UW1(11),XI(101),XI1(11),
     &        Z(101),Z1(11)
C
C     ...PRINT PROBLEM NUMBER AND HEADING
      WRITE(IOUT,100)
      WRITE(IOUT,101)
      WRITE(IOUT,102)
      WRITE(IOUT,103) NPROB
      CALL SETUP
      IF (NPT .EQ. 2) RETURN
      IF (NBL .EQ. 2) GOTO 2
C     ...PRINT SOIL DATA FOR COMPRESSIBLE FOUNDATION
      WRITE(IOUT,104)
      WRITE(IOUT,105)
      WRITE(IOUT,106)
      WRITE(IOUT,107) HBL,GSBL,WL1,Q0
      WRITE(IOUT,108)
      WRITE(IOUT,109)
      DO 1  I=1,LBL
      WRITE(IOUT,110)  I,ES1(I),RS1(I),RK1(I),PK1(I),BETA1(I),
     &                 DSDE1(I),ALPHA1(I)
    1 CONTINUE
      IF (NBL .EQ. 3) GOTO 4
C     ...PRINT SOIL DATA FOR DREDGED FILL
    2 WRITE(IOUT,111)
      WRITE(IOUT,112)
      WRITE(IOUT,113)
      WRITE(IOUT,114)  HDF,GSDF,WL,E00,GW
      WRITE(IOUT,108)
      WRITE(IOUT,109)
      DO 3  I=1,LDF
      WRITE(IOUT,110)  I,ES(I),RS(I),RK(I),PK(I),BETA(I),
     &                 DSDE(I),ALPHA(I)
    3 CONTINUE
```

```
C     ...PRINT CALCULATION DATA
    4 WRITE(IOUT,115)
      WRITE(IOUT,116)
      WRITE(IOUT,117)
      WRITE(IOUT,118) TAU,E0,ZK0,DU0
C     ...PRINT TABLES OF INITIAL CONDITIONS
      NFLAG = 1
      CALL DATOUT
      NFLAG = 0
C
C     ...FORMATS
  100 FORMAT(1H1/////9X,60(1H*))
  101 FORMAT(9X,49HCONSOLIDATION OF SOFT LAYERS BY FINITE STRAIN -- ,
     &       12HDREDGED FILL)
  102 FORMAT(9X,60(1H*))
  103 FORMAT(/9X,14HPROBLEM NUMBER,I4)
  104 FORMAT(/////18(1H*),37HSOIL DATA FOR COMPRESSIBLE FOUNDATION,
     &       17(1H*))
  105 FORMAT(//6X,5HLAYER,6X,16HSPECIFIC GRAVITY,4X,11HWATER LEVEL,
     &       9X,7HINITIAL)
  106 FORMAT(4X,9HTHICKNESS,8X,9HOF SOLIDS,7X,11HFROM BOTTOM,8X,
     &       9HSURCHARGE)
  107 FORMAT(/4X,F8.3,7X,F8.3,2(10X,F8.3))
  108 FORMAT(//8X,4HVOID,2X,9HEFFECTIVE,3X,5HPERM-,5X,5HK/1+E)
  109 FORMAT(4X,8HI   RATIO,4X,6HSTRESS,3X,8HEABILITY,4X,2HPK,7X,4HBETA,
     &       6X,4HDSDE,5X,5HALPHA)
  110 FORMAT(2X,I3,1X,F6.3,6E10.3)
  111 FORMAT(/////23(1H*),26HSOIL DATA FOR DREDGED FILL,23(1H*))
  112 FORMAT(//5X,5HLAYER,5X,16HSPECIFIC GRAVITY,3X,11HWATER LEVEL,
     &       5X,7HINITIAL,4X,11HUNIT WEIGHT)
  113 FORMAT(3X,9HTHICKNESS,7X,9HOF SOLIDS,6X,11HFROM BOTTOM,
     &       3X,10HVOID RATIO,5X,8HOF WATER)
  114 FORMAT(/2X,F8.3,8X,F8.3,9X,F8.3,5X,F8.3,7X,F6.2)
  115 FORMAT(/////28(1H*),16HCALCULATION DATA,28(1H*))
  116 FORMAT(//8X,3HTAU,10X,11HLOWER LAYER,7X,11HLOWER LAYER,7X,
     &       13HDRAINAGE PATH)
  117 FORMAT(21X,10HVOID RATIO,8X,12HPERMEABILITY,9X,6HLENGTH)
  118 FORMAT(/4X,E11.5,8X,F8.3,9X,E11.5,7X,3HZ =,F8.3)
C
C
      RETURN
      END
C
C
```

```
      SUBROUTINE SETUP

      ******************************************************
      * SETUP MAKES INITIAL CALCULATIONS AND MANIPULATIONS *
      * OF INPUT DATA FOR LATER USE.                       *
      ******************************************************

      COMMON   DA,DU0,DUDZ10,DUDZ11,DUDZ21,DZ,DZ1,D0,E0,E00,ELL,ELL1,
     &         GC,GC1,GS,GS1,GSBL,GSDF,GW,HBL,HDF,HDF1,IN,INS,IOUT,
     &         IOUTS,LBL,LDF,MTIME,NBDIV,NBDIV1,NBL,ND,NDIV,NDIV1,
     &         NFLAG,NM,NPROB,NPT,NND,NNN,NTIME,PK0,Q0,Q1,SETT,SETT1,
     &         SFIN,SFIN1,TAU,TIME,TPRINT,UCON,UCON1,VRI1,WL,WL1,ZK0,
     &         A(101),A1(11),AF(101),AF1(11),ALPHA(51),ALPHA1(51),
     &         BETA(51),BETA1(51),BF(101),BF1(11),DSDE(51),DSDE1(51),
     &         E(101),E1(101),E11(11),EFIN(101),EFIN1(11),ER(11),
     &         ES(51),ES1(51),EFFSTR(101),EFSTR1(11),F(101),F1(11),
     &         FINT(101),FINT1(11),PK(51),PK1(51),RK(51),RK1(51),
     &         RS(51),RS1(51),TOTSTR(101),TOSTR1(11),U(101),U1(11),
     &         U0(101),U01(11),UW(101),UW1(11),XI(101),XI1(11),
     &         Z(101),Z1(11)

      ...SET CONSTANTS
      NDIV = NBDIV + 1
      ND = NDIV
      GS = GSDF * GW
      GC = GS - GW
      GS1 = GSBL * GW
      GC1 = GS1 - GW
      NDIV1 = NBDIV1 + 1
      PK0 = ZK0 / (1.0+E0)
      DU0 = DU0 / (1.0+E0)
      IF (NBL .EQ. 2) GOTO 10

      ...CALCULATE ELL FOR COMPRESSIBLE FOUNDATION LAYER
      DZZ = 0.0
      NBD = 10 * NBDIV1
      DABL = HBL / FLOAT(NBD)
      EFS = Q0
      DO 4  I=1,NBD
      DO 1  N=2,LBL
      S1 = EFS - RS1(N)
      IF (S1 .LE. 0.0) GOTO 2
    1 CONTINUE
      V = ES1(LBL) ; GOTO 3
    2 NN = N-1
      V = ES1(N)  + (S1*(ES1(NN)-ES1(N))/(RS1(NN)-RS1(N)))
    3 TDZ = DABL / (1.0+V)
      EFS = EFS + GC1*TDZ
      DZZ = DZZ + TDZ
    4 CONTINUE
      ELL1 = DZZ
      DZ1 = ELL1 / FLOAT(NBDIV1)

```

```
C     ...CALCULATE INITIAL COORDINATES AND VOID RATIOS
C     ...FOR COMPRESSIBLE FOUNDATION LAYER
      Z1(1)=0.0 ; A1(1)=0.0 ; XI1(1)=0.0
      EFS = GC1 * ELL1 + 00
      DO 8  I=1,NDIV1
      DO 5  N=2,LBL
      S1 = EFS - RS1(N)
      IF (S1 .LE. 0.0) GOTO 6
    5 CONTINUE
      E11(I) = ES1(LBL) ; GOTO 7
    6 NN = N-1
      E11(I) = ES1(N) + (S1*(ES1(NN)-ES1(N))/(RS1(NN)-RS1(N)))
    7 F1(I) = E11(I)
      ER(I) = E11(I)
      EFS = EFS - GC1*DZ1
    8 CONTINUE
      CALL INTGRL(ER,DZ1,NDIV1,FINT1)
      DO 9  I=2,NDIV1
      Z1(I) = Z1(I-1) + DZ1
      A1(I) = Z1(I) + FINT1(I)
      XI1(I) = A1(I)
    9 CONTINUE
C
C     ...CALCULATE ELL FOR FIRST DREDGED FILL LAYER
   10 ELL = HDF / (1.0+E00)
      IF (NBL .EQ. 3) GOTO 15
C
C     ...CALCULATE INITIAL COORDINATES AND SET VOID RATIOS
      DZ = ELL / FLOAT(NBDIV)
      Z(1)=0.0 ; A(1)=0.0 ; XI(1)=0.0
      E1(1)=E00 ; F(1)=E00 ; E(1)=E00
      DA = HDF / FLOAT(NBDIV)
      DO 11  I=2,NDIV
      II = I-1
      Z(I) = Z(II) + DZ
      A(I) = A(II) + DA
      XI(I) = A(I)
      E1(I) = E00
      F(I) = E00
      E(I) = E00
   11 CONTINUE
C
C     ...CALCULATE FINAL VOID RATIOS FOR DREDGED FILL
      DO 14  I=1,NBDIV
      S1 = GC*(ELL-Z(I))
      IF (S1 .LT. 0.0) S1 = 0.0
      DO 12  N=2,LDF
      S2 = S1 - RS(N)
      IF (S2 .LE. 0.0) GOTO 13
   12 CONTINUE
      EFIN(I) = ES(LDF) ; GOTO 14
   13 NN = N-1
      EFIN(I) = ES(N) + (S2*(ES(NN)-ES(N))/(RS(NN)-RS(N)))
   14 CONTINUE
      EFIN(NDIV) = E00
C
```

```
C     ...CALCULATE FINAL VOID RATIOS FOR FOUNDATION
      IF (NBL .EQ. 2) GOTO 20
   15 C1 = ELL1*GC1 ; C2 = ELL*GC + Q1
      S1 = C1 + C2
      DO 18  I=1,NDIV1
      S2 = S1 - Z1(I)*GC1
      DO 16  N=2,LBL
      S3 = S2 - RS1(N)
      IF (S3 .LE. 0.0) GOTO 17
   16 CONTINUE
      EFIN1(I) = ES1(LBL) ; GOTO 18
   17 NN = N-1
      EFIN1(I) = ES1(N) + (S3*(ES1(NN)-ES1(N))/(RS1(NN)-RS1(N)))
   18 CONTINUE
      IF (NBL .EQ. 3) ER(NDIV1) = EFIN1(NDIV1)
C
C     ...CALCULATE INITIAL STRESSES AND PORE PRESSURES
C     .....FOR FOUNDATION LAYER
      DO 19  I=1,NDIV1
      U01(I) = GW * (WL1-XI1(I))
      U1(I) = C2 - Q0
      UW1(I) = U01(I) + U1(I)
      EFSTR1(I) = C1 - GC1*Z1(I) + Q0
      TOSTR1(I) = EFSTR1(I) + UW1(I)
   19 CONTINUE
C     .....ULTIMATE SETTLEMENT FOR COMPRESSIBLE FOUNDATION
      VRI1 = FINT1(NDIV1)
      CALL INTGRL(EFIN1,DZ1,NDIV1,FINT1)
      SFIN1 = VRI1 - FINT1(NDIV1)
      IF (NBL .EQ. 3) GOTO 25
C
C     .....FOR DREDGED FILL LAYER
   20 DO 21  I=1,NDIV
      U0(I) = GW * (WL-XI(I))
      U(I) = GC * (ELL-Z(I))
      UW(I) = U0(I) + U(I)
      EFFSTR(I) = 0.0
      TOTSTR(I) = UW(I)
   21 CONTINUE
C     .....ULTIMATE SETTLEMENT FOR DREDGED FILL
      CALL INTGRL(EFIN,DZ,NDIV,FINT)
      SFIN = E00*ELL - FINT(NDIV)
C
C     ...CALCULATE FUNCTIONS FOR DREDGED FILL
C     .....PERMEABILITY FUNCTION
      DO 22  I=1,LDF
      PK(I) = PK(I) / (1.0+ES(I))
   22 CONTINUE
```

```
C     .....SLOPE OF PERMEABILITY FUNCTION -- BETA
C     .....AND SLOPE OF EFF STRESS-VOID RATIO CURVE -- DSDE
      CD = ES(2) - ES(1)
      BETA(1) = (PK(2)-PK(1)) / CD
      DSDE(1) = (RS(2)-RS(1)) / CD
      L = LDF - 1
      DO 23  I=2,L
      II=I-1 ; IJ=I+1
      CD = ES(IJ) - ES(II)
      BETA(I) = (PK(IJ)-PK(II)) / CD
      DSDE(I) = (RS(IJ)-RS(II)) / CD
   23 CONTINUE
      CD = ES(LDF) - ES(L)
      BETA(LDF) = (PK(LDF)-PK(L)) / CD
      DSDE(LDF) = (RS(LDF)-RS(L)) / CD
C     .....PERMEABILITY FUNCTION TIMES DSDE -- ALPHA
      DO 24  I=1,LDF
      ALPHA(I) = PK(I) * DSDE(I)
   24 CONTINUE
      IF (NBL .EQ. 2) GOTO 29
C
C     ...CALCULATE FUNCTIONS FOR COMPRESSIBLE FOUNDATION
C     .....PERMEABILITY FUNCTION
   25 DO 26  I=1,LBL
      PK1(I) = RK1(I) / (1.0+ES1(I))
   26 CONTINUE
C     .....SLOPE OF PERMEABILITY FUNCTION -- BETA1
C     .....AND SLOPE OF EFF STRESS-VOID RATIO CURVE -- DSDE1
      CD = ES1(2) - ES1(1)
      BETA1(1) = (PK1(2)-PK1(1)) / CD
      DSDE1(1) = (RS1(2)-RS1(1)) / CD
      L = LBL - 1
      DO 27  I=2,L
      II=I-1 ; IJ=I+1
      CD = ES1(IJ) - ES1(II)
      BETA1(I) = (PK1(IJ)-PK1(II)) / CD
      DSDE1(I) = (RS1(IJ)-RS1(II)) / CD
   27 CONTINUE
      CD = ES1(LBL) - ES1(L)
      BETA1(LBL) = (PK1(LBL)-PK1(L)) / CD
      DSDE1(LBL) = (RS1(LBL)-RS1(L)) / CD
C     .....PERMEABILITY FUNCTION TIMES DSDE -- ALPHA1
      DO 28  I=1,LBL
      ALPHA1(I) = PK1(I) * DSDE1(I)
   28 CONTINUE
C
C     ...CALCULATE BOTTOM BOUNDARY DUDZ
      DUDZ10 = U1(1) / DU0
   29 IF (NBL .EQ. 2) DUDZ10 = U(1) / DU0
C
C     ...COMPUTE VOID RATIO FUNCTION FOR INITIAL VALUES
      CALL VRFUNC
C
C
      RETURN
      END
C
C
```

```
      SUBROUTINE RESET
C
C     ********************************************
C     * RESET UPDATES PREVIOUS CALCULATIONS TO HANDLE *
C     * ADDITIONAL DEPOSITIONS OF DREDGED FILL.       *
C     ********************************************
C
      COMMON  DA,DU0,DUDZ10,DUDZ11,DUDZ21,DZ,DZ1,DQ,E0,E00,ELL,ELL1,
     &        GC,GC1,GS,GS1,GSBL,GSDF,GW,HBL,HDF,HDF1,IN,INS,IOUT,
     &        IOUTS,LBL,LDF,MTIME,NBDIV,NBDIV1,NBL,ND,NDIV,NDIV1,
     &        NFLAG,NM,NPROB,NPT,NND,NNN,NTIME,PK0,Q0,Q1,SETT,SETT1,
     &        SFIN,SFIN1,TAU,TIME,TPRINT,UCON,UCON1,VRI1,WL,WL1,ZK0,
     &        A(101),A1(11),AF(101),AF1(11),ALPHA(51),ALPHA1(51),
     &        BETA(51),BETA1(51),BF(101),BF1(11),DSDE(51),DSDE1(51),
     &        E(101),E1(101),E11(11),EFIN(101),EFIN1(11),ER(11),
     &        ES(51),ES1(51),EFFSTR(101),EFSTR1(11),F(101),F1(11),
     &        FINT(101),FINT1(11),PK(51),PK1(51),RK(51),RK1(51),
     &        RS(51),RS1(51),TOTSTR(101),TOSTR1(11),U(101),U1(11),
     &        U0(101),U01(11),UW(101),UW1(11),XI(101),XI1(11),
     &        Z(101),Z1(11)
C
      IF (NBL .EQ. 2) WL = WL1
      IF (HDF1 .LE. 0.0) RETURN
      IF (NBL .EQ. 3) Q1 = HDF1 + Q1
      IF (NBL .EQ. 3) GOTO 5
C     ...CALCULATE ELL FOR NEXT DREDGED FILL LAYER AND RESET CONSTANTS
      EL = HDF1 / (1.0+E00)
      IF (NBL .EQ. 2) U(1) = U(1) + EL*GC
      U1(1) = U1(1) + EL*GC
      NDZ = IFIX(EL/DZ)
      ELL = ELL + DZ*FLOAT(NDZ)
      NV = ND + 1
      ND = ND + NDZ
      NB = ND - 1
C     ...CALCULATE ADDITIONAL COORDINATES AND SET VOID RATIOS
      DO 1  I=NV,ND
      II = I-1
      Z(I) = Z(II) + DZ
      A(I) = A(II) + DA
      XI(I) = XI(II) + DA
      E1(I) = E00
      F(I) = E00
      E(I) = E00
    1 CONTINUE
```

```
C     ...CALCULATE FINAL VOID RATIOS FOR DREDGED FILL
      DO 4  I=1,NB
      S1 = GC*(ELL-Z(I))
      IF (S1 .LT. 0.0) S1=0.0
      DO 2  N=2,LDF
      S2 = S1 - RS(N)
      IF (S2 .LE. 0.0) GOTO 3
    2 CONTINUE
      EFIN(I) = ES(LDF) ; GOTO 4
    3 NN = N-1
      EFIN(I) = ES(N) + (S2*(ES(NN)-ES(N))/(RS(NN)-RS(N)))
    4 CONTINUE
      EFIN(ND) = E00
C
C     ...CALCULATE FINAL VOID RATIOS FOR FOUNDATION
      IF (NBL .EQ. 2) GOTO 9
    5 C1 = ELL1*GC1 ; C2 = ELL*GC + Q1
      S1 = C1 + C2
      DO 8  I=1,NDIV1
      S2 = S1 - Z1(I)*GC1
      DO 6  N=2,LBL
      S3 = S2 - RS1(N)
      IF (S3 .LE. 0.0) GOTO 7
    6 CONTINUE
      EFIN1(I) = ES1(LBL) ; GOTO 8
    7 NN = N-1
      EFIN1(I) = ES1(N) + (S3*(ES1(NN)-ES1(N))/(RS1(NN)-RS1(N)))
    8 CONTINUE
C     .....ULTIMATE SETTLEMENT FOR COMPRESSIBLE FOUNDATION
      CALL INTGRL(EFIN1,DZ1,NDIV1,FINT1)
      SFIN1 = VRI1 - FINT1(NDIV1)
C
C     ...RESET BOTTOM BOUNDARY DUDZ
      IF (NBL .EQ. 3) U1(1) = U1(1) + HDF1
      DUDZ10 = U1(1) / DU0
      IF (NBL .EQ. 3) RETURN
    9 IF (NBL .EQ. 2) DUDZ10 = U(1) / DU0
C
C     .....ULTIMATE SETLEMENT FOR TOTAL DREDGED FILL
      CALL INTGRL(EFIN,DZ,ND,FINT)
      SFIN = E00*ELL - FINT(ND)
C
C     ...SET VOID RATIO FUNCTIONS FOR RESET VALUES
      N = NV-1
      DO 10  I=NV,ND
      AF(I) = AF(N)
      BF(I) = BF(N)
   10 CONTINUE
C
C
      RETURN
      END
C
C
```

```
      SUBROUTINE FDIFEQ
C
C     ****************************************************************
C     * FDIFEQ CALCULATES NEW VOID RATIOS AS CONSOLIDATION PROCEEDS *
C     * BY AN EXPLICIT FINITE DIFFERENCE SCHEME BASED ON PREVIOUS    *
C     * VOID RATIOS.  SOIL PARAMETER FUNCTIONS ARE CONSTANTLY        *
C     * UPDATED TO CORRESPOND WITH CURRENT VOID RATIO.               *
C     ****************************************************************
C
      COMMON  DA,DU0,DUDZ10,DUDZ11,DUDZ21,DZ,DZ1,D0,E0,E00,ELL,ELL1,
     &        GC,GC1,GS,GS1,GSBL,GSDF,GW,HBL,HDF,HDF1,IN,INS,IOUT,
     &        IOUTS,LBL,LDF,MTIME,NBDIV,NBDIV1,NBL,ND,NDIV,NDIV1,
     &        NFLAG,NM,NPROB,NPT,NND,NNN,NTIME,PK0,Q0,Q1,SETT,SETT1,
     &        SFIN,SFIN1,TAU,TIME,TPRINT,UCON,UCON1,VRI1,WL,WL1,ZK0,
     &        A(101),A1(11),AF(101),AF1(11),ALPHA(51),ALPHA1(51),
     &        BETA(51),BETA1(51),BF(101),BF1(11),DSDE(51),DSDE1(51),
     &        E(101),E1(101),E11(11),EFIN(101),EFIN1(11),ER(11),
     &        ES(51),ES1(51),EFFSTR(101),EFSTR1(11),F(101),F1(11),
     &        FINT(101),FINT1(11),PK(51),PK1(51),RK(51),RK1(51),
     &        RS(51),RS1(51),TOTSTR(101),TOSTR1(11),U(101),U1(11),
     &        U0(101),U01(11),UW(101),UW1(11),XI(101),XI1(11),
     &        Z(101),Z1(11)
C
C     ...SET CONSTANTS
      CF = TAU/(GW*DZ)
      DZ2 = DZ*2.0
      NND = ND - 1
      IF (NBL .EQ. 2) GOTO 5
      DZ12 = DZ1*2.0
      CF1 = TAU/(GW*DZ1)
      IF (NBL .EQ. 3) ER(NDIV1) = EFIN1(NDIV1)
C
C     .LOOP THROUGH FINITE DIFFERENCE EQUATIONS UNTIL PRINT TIME
C
C     ...CALCULATE VOID RATIO OF IMAGE POINT AND FIRST REAL POINT
C     .....FOR COMPRESSIBLE LAYER
    1 DO 2  I=2,LBL
      C1 = ER(1) - ES1(I)
      IF (C1 .GE. 0.0) GOTO 3
    2 CONTINUE
      DSED = DSDE1(LBL) ; GOTO 4
    3 II = I-1
      DSED = DSDE1(I) + (C1*(DSDE1(I)-DSDE1(II))/(ES1(I)-ES1(II)))
    4 F10 = F1(2) + DZ12*(GC1+DUDZ11)/DSED
      DF = (F1(2)-F10) / 2.0
      DF2DZ = (F1(2)-2.0*F1(1)+F10) / DZ1
      AC = (AF1(2)-AF1(1)) / DZ1
      ER(1) = F1(1) - CF1*(DF*(GC1*BF1(1)+AC)+DF2DZ*AF1(1))
      IF (ER(1) .LT. EFIN1(1))  ER(1) = EFIN1(1)
      IF (ER(1) .GT. E11(1))  ER(1) = E11(1)
      IF (NBL .EQ. 3) GOTO 24
```

```
C     .....FOR DREDGED FILL
    5 DO 6  I=2,LDF
      C1 = E(1) - ES(I)
      IF (C1 .GE. 0.0) GOTO 7
    6 CONTINUE
      DSED = DSDE(LDF) ; GOTO 8
    7 II = I-1
      DSED = DSDE(I) + (C1*(DSDE(I)-DSDE(II))/(ES(I)-ES(II)))
    8 F0 = F(2) + DZ2*(GC+DUDZ21)/DSED
      DF = (F(2)-F0) / 2.0
      DF2DZ = (F(2)-2.0*F(1)+F0) / DZ
      AC = (AF(2)-AF(1)) / DZ
      E(1) = F(1) - CF*(DF*(GC*BF(1)+AC)+DF2DZ*AF(1))
      IF (E(1) .LT. EFIN(1))  E(1) = EFIN(1)
C
C     ...CALCULATE VOID RATIO OF TOP POINT IN COMPRESSIBLE LAYER
      IF (NBL .EQ. 2) GOTO 27
      DO 9  I=2,LDF
      C1 = E(1) - ES(I)
      IF (C1 .GE. 0.0) GOTO 10
    9 CONTINUE
      EST = RS(LDF) ; GOTO 11
   10 II = I-1
      EST = RS(I) + (C1*(RS(I)-RS(II))/(ES(I)-ES(II)))
   11 DEST = EST - EFFSTR(1)
      UT = U(1) - DEST
      EFS1 = EFSTR1(NDIV1) + DEST
      DO 12  I=2,LBL
      C1 = EFS1 - RS1(I)
      IF (C1 .LE. 0.0) GOTO 13
   12 CONTINUE
      ER(NDIV1) = ES1(LBL) ; GOTO 14
   13 II = I-1
      ER(NDIV1) = ES1(I) + (C1*(ES1(II)-ES1(I))/(RS1(II)-RS1(I)))
C
C     ...RESET BOUNDARY DUDZ FOR DREDGED FILL
   14 DO 15  I=2,LBL
      C1 = ER(NBDIV1) - ES1(I)
      IF (C1 .GE. 0.0) GOTO 16
   15 CONTINUE
      EST1= RS1(LBL) ; GOTO 17
   16 II = I-1
      EST1 = RS1(I) + (C1*(RS1(I)-RS1(II))/(ES1(I)-ES1(II)))
   17 UT1 = U1(NBDIV1) - EST1 + EFSTR1(NBDIV1)
      DUDZ12 = (UT - UT1) / DZ1
      DO 18  I=2,LBL
      C1 = ER(NDIV1) - ES1(I)
      IF (C1 .GE. 0.0) GOTO 19
   18 CONTINUE
      RPKER = PK1(LBL) ; GOTO 20
   19 II = I-1
      RPKER = PK1(I) + (C1*(PK1(I)-PK1(II))/(ES1(I)-ES1(II)))
   20 DO 21  I=2,LDF
      C1 = E(1) - ES(I)
      IF (C1 .GE. 0.0) GOTO 22
   21 CONTINUE
      PKE = PK(LDF) ; GOTO 23
   22 II = I-1
      PKE = PK(I) + (C1*(PK(I)-PK(II))/(ES(I)-ES(II)))
   23 DUDZ21 = DUDZ12 * RPKER / PKE
C
```

```
C     ...CALCULATE NEW VOID RATIOS FOR REMAINDER OF MATERIAL
C     .....IN COMPRESSIBLE FOUNDATION
   24 DO 25  I=2,NBDIV1
      II = I-1 ; IJ = I+1
      DF = (F1(IJ)-F1(II)) / 2.0
      DF2DZ = (F1(IJ)-F1(I)*2.0+F1(II)) / DZ1
      AC = (AF1(IJ)-AF1(II)) / DZ12
      ER(I) = F1(I) - CF1*(DF*(GC1*BF1(I)+AC)+DF2DZ*AF1(I))
   25 CONTINUE
C     .....RESET FOR NEXT LOOP
      DO 26  I=1,NDIV1
      F1(I) = ER(I)
   26 CONTINUE
      IF (NBL .EQ. 3) GOTO 30
C
C     ...NEW VOID RATIOS IN DREDGED FILL
   27 DO 28  I=2,NND
      II = I-1 ; IJ = I+1
      DF = (F(IJ)-F(II)) / 2.0
      DF2DZ = (F(IJ)-F(I)*2.0+F(II)) / DZ
      AC = (AF(IJ)-AF(II)) / DZ2
      E(I) = F(I) - CF*(DF*(GC*BF(I)+AC)+DF2DZ*AF(I))
   28 CONTINUE
C     .....RESET FOR NEXT LOOP
      DO 29  I=1,NND
      F(I) = E(I)
   29 CONTINUE
C
C     ...RESET BOTTOM BOUNDARY DUDZ FOR COMPRESSIBLE LAYER
      IF (NBL .EQ. 2) GOTO 34
   30 DO 31  I=2,LBL
      C1 = ER(1) - ES1(I)
      IF (C1 .GE. 0.0) GOTO 32
   31 CONTINUE
      RPKER = PK1(LBL)
      EST1 = RS1(LBL) ; GOTO 33
   32 II = I-1
      C2 = C1 / (ES1(I)-ES1(II))
      RPKER = PK1(I) + C2*(PK1(I)-PK1(II))
      EST1 = RS1(I) + C2*(RS1(I)-RS1(II))
   33 DUDZ11 = DUDZ10 * PK0 / RPKER
      UT1 = U1(1) - EST1 + EFSTR1(1)
      DUDZ10 = UT1 / DU0
      GOTO 38
C
```

```
C     ...RESET BOTTOM BOUNDARY DUDZ FOR DREDGED FILL
   34 DO 35  I=2,LDF
      C1 = E(1) - ES(I)
      IF (C1 .GE. 0.0) GOTO 36
   35 CONTINUE
      PKE = PK(LDF)
      EST = RS(LDF) ; GOTO 37
   36 II = I-1
      C2 = C1 / (ES(I)-ES(II))
      PKE = PK(I) + C2*(PK(I)-PK(II))
      EST = RS(I) + C2*(RS(I)-RS(II))
   37 DUDZ21 = DUDZ10 * PK0 / PKE
      UT = U(1) - EST + EFFSTR(1)
      DUDZ10 = UT / DU0
C
C     ...CALCULATE ALPHA AND BETA FOR CURRENT VOID RATIOS
   38 CALL VRFUNC
C
C     ...CALCULATE CURRENT TIME AND CHECK AGAINST PRINT TIME
      TIME = TAU * FLOAT(NNN)
      NNN = NNN + 1
      IF (TIME .LT. TPRINT .AND. NBL .EQ. 1) GOTO 1
      IF (TIME .LT. TPRINT .AND. NBL .EQ. 2) GOTO 5
      IF (TIME .LT. TPRINT .AND. NBL .EQ. 3) GOTO 1
C
C     ...CHECK STABILITY AND CONSISTENCY
      IF (NBL .EQ. 2) GOTO 39
      STAB = ABS((DZ1**2*GW)/(2.0*AF1(1)))
      IF (STAB .LT. TAU) WRITE(IOUT,100) NPROB
      CONS = ABS((2.0*AF1(1))/(GC1*BF1(1)))
      IF (CONS .LE. DZ1) WRITE(IOUT,101) NPROB
      IF (NBL .EQ. 3) RETURN
   39 STAB = ABS((DZ**2*GW)/(2.0*AF(1)))
      IF (STAB .LT. TAU) WRITE(IOUT,102) NPROB
      CONS = ABS((2.0*AF(1))/(GC*BF(1)))
      IF (CONS .LE. DZ) WRITE(IOUT,103) NPROB
C
C     ...FORMATS
  100 FORMAT(/////38HSTABILITY ERROR --FOUNDATION --PROBLEM,I5)
  101 FORMAT(/////40HCONSISTENCY ERROR --FOUNDATION --PROBLEM,I5)
  102 FORMAT(/////40HSTABILITY ERROR --DREDGED FILL --PROBLEM,I5)
  103 FORMAT(/////42HCONSISTENCY ERROR --DREDGED FILL --PROBLEM,I5)
C
C
      RETURN
      END
C
C
```

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      SUBROUTINE VRFUNC
C
C     ********************************************
C     * VRFUNC CALCULATES ALFHA AND BETA FUNCTIONS *
C     * FOR CURRENT VOID RATIOS.                   *
C     ********************************************
C
      COMMON  DA,DU0,DUDZ10,DUDZ11,DUDZ21,DZ,DZ1,DO,E0,E00,ELL,ELL1,
     &        GC,GC1,GS,GS1,GSBL,GSDF,GW,HPL,HDF,HDF1,IN,INS,IOUT,
     &        IOUTS,LBL,LDF,MTIME,NBDIV,NBDIV1,NBL,ND,NDIV,NDIV1,
     &        NFLAG,NM,NPROB,NPT,NND,NNN,NTIME,PK0,Q0,Q1,SETT,SETT1,
     &        SFIN,SFIN1,TAU,TIME,TPRINT,UCON,UCON1,VRI1,WL,WL1,ZK0,
     &        A(101),A1(11),AF(101),AF1(11),ALPHA(51),ALPHA1(51),
     &        BETA(51),BETA1(51),BF(101),BF1(11),DSDE(51),DSDE1(51),
     &        E(101),E1(101),E11(11),EFIN(101),EFIN1(11),ER(11),
     &        ES(51),ES1(51),EFFSTR(101),EFSTR1(11),F(101),F1(11),
     &        FINT(101),FINT1(11),PK(51),PK1(51),RK(51),RK1(51),
     &        RS(51),RS1(51),TOTSTR(101),TOSTR1(11),U(101),U1(11),
     &        U0(101),U01(11),UW(101),UW1(11),XI(101),XI1(11),
     &        Z(101),Z1(11)
C
      IF (NBL .EQ. 2) GOTO 4
C     ...FOR COMPRESSIBLE FOUNDATION
      DO 3  I=1,NDIV1
      DO 1  N=2,LBL
      C1 = ER(I) - ES1(N)
      IF (C1 .GE. 0.0) GOTO 2
    1 CONTINUE
      AF1(I) = ALPHA1(LBL)
      BF1(I) = BETA1(LBL) ; GOTO 3
    2 NN = N-1
      CM = C1 / (ES1(N)-ES1(NN))
      AF1(I) = ALPHA1(N) + CM*(ALPHA1(N)-ALPHA1(NN))
      BF1(I) = BETA1(N) + CM*(BETA1(N)-BETA1(NN))
    3 CONTINUE
      IF (NBL .EQ. 3) RETURN
C
C     ...FOR DREDGED FILL
    4 DO 7  I=1,NND
      DO 5  N=2,LDF
      C1 = E(I) - ES(N)
      IF (C1 .GE. 0.0) GOTO 6
    5 CONTINUE
      AF(I) = ALPHA(LDF)
      BF(I) = BETA(LDF) ; GOTO 7
    6 NN = N-1
      CM = C1 / (ES(N)-ES(NN))
      AF(I) = ALPHA(N) + CM*(ALPHA(N)-ALPHA(NN))
      BF(I) = BETA(N) + CM*(BETA(N)-BETA(NN))
    7 CONTINUE
      AF(ND) = ALPHA(1)
      BF(ND) = BETA(1)
C
C
      RETURN
      END
C
C
```

```
      SUBROUTINE STRESS
C
C     ******************************************************
C     * STRESS CALCULATES EFFECTIVE STRESSES, TOTAL STRESSES, *
C     * AND PORE WATER PRESSURES BASED ON CURRENT VOID RATIO  *
C     * AND VOID RATIO INTEGRAL.                              *
C     ******************************************************
C
      COMMON  DA,DU0,DUDZ10,DUDZ11,DUDZ21,DZ,DZ1,D0,E0,E00,ELL,ELL1,
     &        GC,GC1,GS,GS1,GSBL,GSDF,GW,HBL,HDF,HDF1,IN,INS,IOUT,
     &        IOUTS,LBL,LDF,MTIME,NBDIV,NBDIV1,NBL,ND,NDIV,NDIV1,
     &        NFLAG,NM,NPROB,NPT,NND,NNN,NTIME,PK0,Q0,Q1,SETT,SETT1,
     &        SFIN,SFIN1,TAU,TIME,TPRINT,UCON,UCON1,VR11,WL,WL1,ZK0,
     &        A(101),A1(11),AF(101),AF1(11),ALPHA(51),ALPHA1(51),
     &        BETA(51),BETA1(51),BF(101),BF1(11),DSDE(51),DSDE1(51),
     &        E(101),E1(101),E11(11),EFIN(101),EFIN1(11),ER(11),
     &        ES(51),ES1(51),EFFSTR(101),EFSTR1(11),F(101),F1(11),
     &        FINT(101),FINT1(11),PK(51),PK1(51),RK(51),RK1(51),
     &        RS(51),RS1(51),TOTSTR(101),TOSTR1(11),U(101),U1(11),
     &        U0(101),U01(11),UW(101),UW1(11),XI(101),XI1(11),
     &        Z(101),Z1(11)
C
C     ...CALCULATE VOID RATIO INTEGRAL
      IF (NBL .EQ. 3) GOTO 1
      CALL INTGRL(E,DZ,ND,FINT)
      IF (NBL .EQ. 2) GOTO 7
    1 CALL INTGRL(ER,DZ1,NDIV1,FINT1)
C
C     ...FOR COMPRESSIBLE FOUNDATION
C     .....CALCULATE XI COORDINATES AND STRESSES
      DO 2  I=1,NDIV1
      XI1(I) = Z1(I) + FINT1(I)
    2 CONTINUE
      WL = WL1 - XI1(NDIV1)
      G1 = ELL * GC + Q1
      W1 = FINT1(NDIV1) + WL
      DO 6  I=1,NDIV1
      DO 3  N=2,LBL
      C1 = ER(I) - ES1(N)
      IF (C1 .GE. 0.0) GOTO 4
    3 CONTINUE
      EFSTR1(I) = RS1(LBL) ; GOTO 5
    4 NN = N-1
      EFSTR1(I) = RS1(N) + (C1*(RS1(N)-RS1(NN))/(ES1(N)-ES1(NN)))
    5 U01(I) = GW * (WL1-XI1(I))
      TOSTR1(I) = GW*(W1-FINT1(I)) + GS1*(ELL1-Z1(I)) + G1
      UW1(I) = TOSTR1(I) - EFSTR1(I)
      U1(I) = UW1(I) - U01(I)
    6 CONTINUE
      IF (NBL .EQ. 3) GOTO 13
C
```

```
C     ...FOR DREDGED FILL
C     .....CALCULATE XI COORDINATES AND STRESSES
    7 DO 8  I=1,ND
      XI(I) = Z(I) + FINT(I)
    8 CONTINUE
      WLL = WL - XI(ND)
      W1 = FINT(ND) + WLL
      DO 12  I=1,ND
      DO 9  N=2,LDF
      C1 = E(I) -ES(N)
      IF (C1 .GE. 0.0) GOTO 10
    9 CONTINUE
      EFFSTR(I) = RS(LDF) : GOTO 11
   10 NN = N-1
      EFFSTR(I) = RS(N) + (C1*(RS(N)-RS(NN))/(ES(N)-ES(NN)))
   11 U0(I) = GW * (WL-XI(I))
      TOTSTR(I) = GW*(W1-FINT(I)) + GS*(ELL-Z(I))
      UW(I) = TOTSTR(I) - EFFSTR(I)
      U(I) = UW(I) - U0(I)
   12 CONTINUE
C
C     ...CALCULATE SETTLEMENT AND DEGREE OF CONSOLIDATION
      IF (NBL .EQ. 2) GOTO 14
   13 SETT1 = A1(NDIV1) - XI1(NDIV1)
      UCON1 = SETT1 / SFIN1
      IF (NBL .EQ. 3) RETURN
   14 SETT = A(ND) - XI(ND)
      UCON = SETT / SFIN
C
C
      RETURN
      END
C
C
```

```
      SUBROUTINE INTGRL(E,DZ,N,F)

      ********************************************
      * INTGRL EVALUATES THE VOID RATIO INTEGRAL TO *
      * EACH MESH POINT IN THE MATERIAL.            *
      ********************************************

      DIMENSION E(101),F(101)
      ...BY SIMPSONS RULE FOR ALL ODD NUMBERED MESH POINTS
      F(1) = 0.0
      DO 1  I=3,N,2
      F(I) = F(I-2) + DZ*(E(I-2)+4.0*E(I-1)+E(I))/3.0
    1 CONTINUE
      ...BY SIMPSONS 3/8 RULE FOR EVEN NUMBERED MESH POINTS
      DO 2  I=4,N,2
      F(I) = F(I-3) + DZ*(E(I-3)+3.0*(E(I-2)+E(I-1))+E(I))*(3.0/8.0)
    2 CONTINUE
      ...BY DIFFERENCES FOR FIRST INTERVAL
      F2 = DZ*(E(2)+4.0*E(3)+E(4))/3.0
      F(2) = F(4) -F2


      RETURN
      END
```

```
      SUBROUTINE DATOUT

      ************************************************************
      * DATOUT PRINTS RESULTS OF CONSOLIDATION CALCULATIONS AND  *
      * BASE DATA IN TABULAR FORM.                                *
      ************************************************************

      COMMON   DA,DU0,DUDZ10,DUDZ11,DUDZ21,DZ,DZ1,D0,E0,E00,ELL,ELL1,
     &         GC,GC1,GS,GS1,GSBL,GSDF,GW,HBL,HDF,HDF1,IN,INS,IOUT,
     &         IOUTS,LBL,LDF,MTIME,NBDIV,NBDIV1,NBL,ND,NDIV,NDIV1,
     &         NFLAG,NM,NPROB,NPT,NND,NNN,NTIME,PK0,Q0,Q1,SETT,SETT1,
     &         SFIN,SFIN1,TAU,TIME,TPRINT,UCON,UCON1,VRI1,WL,WL1,ZK0,
     &         A(101),A1(11),AF(101),AF1(11),ALPHA(51),ALPHA1(51),
     &         BETA(51),BETA1(51),BF(101),BF1(11),DSDE(51),DSDE1(51),
     &         E(101),E1(101),E11(11),EFIN(101),EFIN1(11),ER(11),
     &         ES(51),ES1(51),EFFSTR(101),EFSTR1(11),F(101),F1(11),
     &         FINT(101),FINT1(11),PK(51),PK1(51),RK(51),RK1(51),
     &         RS(51),RS1(51),TOTSTR(101),TOSTR1(11),U(101),U1(11),
     &         U0(101),U01(11),UW(101),UW1(11),XI(101),XI1(11),
     &         Z(101),Z1(11)

      ...PRINT CONDITIONS IN COMPRESSIBLE FOUNDATION
      IF (NBL .EQ. 2) GOTO 3
      IF (NFLAG .EQ. 1) WRITE(IOUT,100)
      IF (NFLAG .EQ. 0) WRITE(IOUT,108)
      WRITE(IOUT,101)
      WRITE(IOUT,102)
      DO 1  I=1,NDIV1
      J = NDIV1+1-I
      WRITE(IOUT,103) A1(J),XI1(J),Z1(J),E11(J),ER(J),EFIN1(J)
    1 CONTINUE
      WRITE(IOUT,104)
      WRITE(IOUT,105)
      DO 2  I=1,NDIV1
      J = NDIV1+1-I
      WRITE(IOUT,103) XI1(J),TOSTR1(J),EFSTR1(J),UW1(J),U01(J),U1(J)
    2 CONTINUE
      WRITE(IOUT,107) TIME,UCON1
      WRITE(IOUT,110) SETT1,SFIN1
      WRITE(IOUT,111) DUDZ11
      WRITE(IOUT,112) WL1
      IF (NBL .EQ. 3) RETURN

```

```
C     ...PRINT CONDITIONS IN DREDGED FILL
    3 IF (NFLAG .EQ. 1) WRITE(IOUT,106)
      IF (NFLAG .EQ. 0) WRITE(IOUT,109)
      WRITE(IOUT,101)
      WRITE(IOUT,102)
      DO 4  I=1,ND
      J = ND+1-I
      WRITE(IOUT,103) A(J),XI(J),Z(J),E1(J),E(J),EFIN(J)
    4 CONTINUE
      WRITE(IOUT,104)
      WRITE(IOUT,105)
      DO 5  I=1,ND
      J = ND+1-I
      WRITE(IOUT,103) XI(J),TOTSTR(J),EFFSTR(J),UW(J),U0(J),U(J)
    5 CONTINUE
      WRITE(IOUT,107) TIME,UCON
      WRITE(IOUT,110) SETT,SFIN
      WRITE(IOUT,111) DUDZ21
      WRITE(IOUT,112) WL
C
C     ...FORMATS
  100 FORMAT(1H1/////14(1H*),34HINITIAL CONDITIONS IN COMPRESSIBLE,
     &         11H FOUNDATION,13(1H*))
  101 FORMAT(//8X,5(1H*),13H COORDINATES ,5(1H*),13X,5(1H*),
     &         13H VOID RATIOS ,5(1H*))
  102 FORMAT(/7X,1HA,10X,2HXI,11X,1HZ,7X,8HEINITIAL,8X,1HE,8X,
     &         6HEFINAL)
  103 FORMAT(2X,5(F10.4,2X),F10.4)
  104 FORMAT(//15X,5(1H*),10H STRESSES ,5(1H*),7X,5(1H*),
     &         16H PORE PRESSURES ,5(1H*))
  105 FORMAT(/6X,2HXI,9X,5HTOTAL,5X,9HEFFECTIVE,5X,5HTOTAL,6X,
     &         6HSTATIC,6X,6HEXCESS)
  106 FORMAT(1H1/////19(1H*),34HINITIAL CONDITIONS IN DREDGED FILL,
     &         19(1H*))
  107 FORMAT(//10X,7HTIME = ,E10.4,5X,26HDEGREE OF CONSOLIDATION = ,
     &         F10.6)
  108 FORMAT(1H1/////14(1H*),34HCURRENT CONDITIONS IN COMPRESSIBLE,
     &         11H FOUNDATION,13(1H*))
  109 FORMAT(1H1/////19(1H*),34HCURRENT CONDITIONS IN DREDGED FILL,
     &         19(1H*))
  110 FORMAT(/10X,13HSETTLEMENT = ,F10.4,5X,19HFINAL SETTLEMENT = ,
     &         F10.4)
  111 FORMAT(/10X,27HBOTTOM BOUNDARY GRADIENT = ,F10.4)
  112 FORMAT(/10X,27HWATER LEVEL ABOVE BOTTOM = ,F10.4)
C
C
      RETURN
      END
```

```
      SUBROUTINE  DATAIN
C
C     ****************************************************
C     * DATAIN READS THE DATA FROM A PREVIOUS PROGRAM RUN FROM *
C     * FILE SO THAT FUTURE CONSOLIDATION CAN BE CALCULATED    *
C     * WITHOUT REDOING ALL PREVIOUS.                          *
C     ****************************************************
C
      COMMON  DA,DU0,DUDZ10,DUDZ11,DUDZ21,DZ,DZ1,D0,E0,E00,ELL,ELL1,
     &        GC,GC1,GS,GS1,GSBL,GSDF,GW,HBL,HDF,HDF1,IN,INS,IOUT,
     &        IOUTS,LBL,LDF,MTIME,NBDIV,NBDIV1,NBL,ND,NDIV,NDIV1,
     &        NFLAG,NM,NPROB,NPT,NND,NNN,NTIME,PK0,Q0,Q1,SETT,SETT1,
     &        SFIN,SFIN1,TAU,TIME,TPRINT,UCON,UCON1,VPI1,WL,WL1,ZK0,
     &        A(101),A1(11),AF(101),AF1(11),ALPHA(51),ALPHA1(51),
     &        BETA(51),BETA1(51),BF(101),BF1(11),DSDE(51),DSDE1(51),
     &        E(101),E1(101),E11(11),EFIN(101),EFIN1(11),ER(11),
     &        ES(51),ES1(51),EFFSTR(101),EFSTR1(11),F(101),F1(11),
     &        FINT(101),FINT1(11),PK(51),PK1(51),RK(51),RK1(51),
     &        PS(51),PS1(51),TOTSTR(101),TOTSTR1(11),U(101),U1(11),
     &        U0(101),U01(11),UW(101),UW1(11),XI(101),XI1(11),
     &        Z(101),Z1(11)
C
      READ(INS,100) NST,IN,INS,IOUT,IOUTS,LBL,LDF
      READ(INS,100) NST,NBDIV,NBDIV1,NDIV,NDIV1,NBL
      READ(INS,100) NST,ND,NFLAG,NM,NND,NNN,NTIME
      READ(INS,200) NST,DA,DUDZ11,DUDZ21,DZ,DZ1
      READ(INS,200) NST,E00,ELL,ELL1,GC,GC1
      READ(INS,200) NST,GS,GS1,GSBL,GSDF,GW
      READ(INS,200) NST,HBL,HDF,HDF1,SETT,SETT1
      READ(INS,200) NST,SFIN,SFIN1,TAU,TPRINT
      READ(INS,200) NST,UCON,UCON1,VPI1,WL,WL1
      READ(INS,200) NST,DU0,DUDZ10,D0,E0
      READ(INS,200) NST,ZK0,PK0,Q0,Q1
C
      IF (NBL .EQ. 3) GOTO 2
      DO 1  I=1,ND
      READ(INS,200) NST,A(I),AF(I),BF(I),E(I),E1(I)
      READ(INS,200) NST,EFIN(I),EFFSTR(I),F(I),FINT(I),TOTSTR(I)
      READ(INS,200) NST,U(I),U0(I),UW(I),XI(I),Z(I)
    1 CONTINUE
      IF (NBL .EQ. 2) GOTO 4
```

```
C
    2 DO 3  I=1,NDIV1
      READ(INS,200) NST,A1(I),AF1(I),BF1(I),ER(I),E11(I)
      READ(INS,200) NST,EFIN1(I),EFSTR1(I),F1(I),FINT1(I),TOSTR1(I)
      READ(INS,200) NST,U1(I),U01(I),UW1(I),XI1(I),Z1(I)
    3 CONTINUE
      IF (NBL .EQ. 3) GOTO 6
C
    4 DO 5  I=1,LDF
      READ(INS,200) NST,ALPHA(I),BETA(I),DSDE(I),ES(I),PK(I)
      READ(INS,200) NST,RK(I),RS(I)
    5 CONTINUE
      IF (NBL .EQ. 2) GOTO 8
C
    6 DO 7  I=1,LBL
      READ(INS,200) NST,ALPHA1(I),BETA1(I),DSDE1(I),ES1(I),PK1(I)
      READ(INS,200) NST,RK1(I),RS1(I)
    7 CONTINUE
C
C     ...RESET TIME CONTROL
    8 NM = NTIME + 1
      NTIME = NTIME + MTIME
      WRITE(IOUT,300) NPROB
C
C     ...FORMATS
  100 FORMAT(I5,7I9)
  200 FORMAT(I5,5E13.6)
  300 FORMAT(/9X,30HCONTINUATION OF PROBLEM NUMBER,I4)
C
      RETURN
      END
C
C
```

```
      SUBROUTINE  SAVDAT

      ******************************************************
      * SAVDAT SAVES THE DATA FROM A PREVIOUS PROGRAM RUN ON  *
      * FILE SO THAT FUTURE EXTENSIONS TO THE RUN MAY BE MADE *
      * WITHOUT RECALCULATING PREVIOUS CONSOLIDATION.         *
      ******************************************************

      COMMON   DA,DU0,DUDZ10,DUDZ11,DUDZ21,DZ,DZ1,D0,E0,E00,ELL,ELL1,
     &         GC,GC1,GS,GS1,GSBL,GSDF,GW,HBL,HDF,HDF1,IN,INS,IOUT,
     &         IOUTS,LBL,LDF,MTIME,NBDIV,NBDIV1,NBL,ND,NDIV,NDIV1,
     &         NFLAG,NM,NPROB,NPT,NND,NNN,NTIME,PK0,Q0,Q1,SETT,SETT1,
     &         SFIN,SFIN1,TAU,TIME,TPRINT,UCON,UCON1,VRI1,WL,WL1,ZK0,
     &         A(101),A1(11),AF(101),AF1(11),ALPHA(51),ALPHA1(51),
     &         BETA(51),BETA1(51),BF(101),BF1(11),DSDE(51),DSDE1(51),
     &         E(101),E1(101),E11(11),EFIN(101),EFIN1(11),ER(11),
     &         ES(51),ES1(51),EFFSTR(101),EFSTR1(11),F(101),F1(11),
     &         FINT(101),FINT1(11),PK(51),PK1(51),RK(51),RK1(51),
     &         RS(51),RS1(51),TOTSTR(101),TOSTR1(11),U(101),U1(11),
     &         U0(101),U01(11),UW(101),UW1(11),XI(101),XI1(11),
     &         Z(101),Z1(11)

      NST = 1
      WRITE(IOUTS,100) NST,IN,INS,IOUT,IOUTS,LBL,LDF
      NST = NST + 1
      WRITE(IOUTS,100) NST,NBDIV,NBDIV1,NDIV,NDIV1,NBL
      NST = NST + 1
      WRITE(IOUTS,100) NST,ND,NFLAG,NM,NND,NNN,NTIME
      NST = NST + 1
      WRITE(IOUTS,200) NST,DA,DUDZ11,DUDZ21,DZ,DZ1
      NST = NST + 1
      WRITE(IOUTS,200) NST,E00,ELL,ELL1,GC,GC1
      NST = NST + 1
      WRITE(IOUTS,200) NST,GS,GS1,GSBL,GSDF,GW
      NST = NST + 1
      WRITE(IOUTS,200) NST,HBL,HDF,HDF1,SETT,SETT1
      NST = NST + 1
      WRITE(IOUTS,200) NST,SFIN,SFIN1,TAU,TIME,TPRINT
      NST = NST + 1
      WRITE(IOUTS,200) NST,UCON,UCON1,VRI1,WL,WL1
      NST = NST + 1
      WRITE(IOUTS,200) NST,DU0,DUDZ10,D0,E0
      NST = NST + 1
      WRITE(IOUTS,200) NST,ZK0,PK0,Q0,Q1
```

```
      IF (NBL .EQ. 3) GOTO 2
      DO 1  I=1,ND
      NST = NST + 1
      WRITE(IOUTS,200) NST,A(I),AF(I),BF(I),E(I),E1(I)
      NST = NST + 1
      WRITE(IOUTS,200) NST,EFIN(I),EFFSTR(I),F(I),FINT(I),TOTSTR(I)
      NST = NST + 1
      WRITE(IOUTS,200) NST,U(I),U0(I),UW(I),XI(I),Z(I)
    1 CONTINUE
      IF (NBL .EQ. 2) GOTO 4
C
    2 DO 3  I=1,NDIV1
      NST = NST + 1
      WRITE(IOUTS,200) NST,A1(I),AF1(I),BF1(I),ER(I),E11(I)
      NST = NST + 1
      WRITE(IOUTS,200) NST,EFIN1(I),EFSTR1(I),F1(I),FINT1(I),TOTSTR1(I)
      NST = NST + 1
      WRITE(IOUTS,200) NST,U1(I),U01(I),UW1(I),XI1(I),Z1(I)
    3 CONTINUE
      IF (NBL .EQ. 3) GOTO 6
C
    4 DO 5  I=1,LDF
      NST = NST + 1
      WRITE(IOUTS,200) NST,ALPHA(I),BETA(I),DSDE(I),ES(I),PK(I)
      NST = NST + 1
      WRITE(IOUTS,200) NST,PK(I),RS(I)
    5 CONTINUE
      IF (NBL .EQ. 2) RETURN
C
    6 DO 7  I=1,LBL
      NST = NST + 1
      WRITE(IOUTS,200) NST,ALPHA1(I),BETA1(I),DSDE1(I),ES1(I),PK1(I)
      NST = NST + 1
      WRITE(IOUTS,200) NST,PK1(I),RS1(I)
    7 CONTINUE
C
C     ...FORMATS
  100 FORMAT(I5,7I9)
  200 FORMAT(I5,5E13.6)
C
      RETURN
      END
```

APPENDIX C: SAMPLE PROBLEM LISTINGS

1. The following pages contain sample data input and calculation results from the two practical applications previously discussed.

2. This page and the next contain the input data file used in the dredged fill with compressible foundation example.

```
100      10  1  2
101       2  1
200      2.83  20.0  25.0  36  0.0  0.0
201      3.00     0.0  1.210E-03
202      2.95     4.2  1.112E-03
203      2.90     8.8  1.030E-03
204      2.85    14.0  9.494E-04
205      2.80    19.6  8.854E-04
206      2.75    25.4  8.234E-04
207      2.70    32.0  7.616E-04
208      2.65    39.0  7.000E-04
209      2.60    48.0  6.392E-04
210      2.55    58.0  5.788E-04
211      2.50    70.0  5.227E-04
212      2.45    86.0  4.680E-04
213      2.40   104.0  4.234E-04
214      2.35   128.0  3.830E-04
215      2.30   154.0  3.456E-04
216      2.25   190.0  3.096E-04
217      2.20   232.0  2.736E-04
218      2.15   288.0  2.448E-04
219      2.10   344.0  2.160E-04
220      2.05   420.0  1.944E-04
221      2.00   510.0  1.714E-04
222      1.95   640.0  1.512E-04
223      1.90   780.0  1.325E-04
224      1.85   950.0  1.170E-04
225      1.80  1160.0  1.034E-04
226      1.75  1400.0  9.000E-05
227      1.70  1700.0  7.720E-05
228      1.65  2040.0  6.624E-05
229      1.60  2540.0  5.832E-05
230      1.55  3100.0  5.112E-05
231      1.50  3750.0  4.392E-05
232      1.45  4600.0  3.773E-05
233      1.40  5540.0  3.197E-05
234      1.35  6800.0  2.736E-05
235      1.30  8400.0  2.333E-05
236      1.25 10400.0  1.987E-05
```

```
300      2.75  3.0  5.0  31  7.0  62.4
301      7.00     0.0  8.568E-03
302      6.95     0.3  8.208E-03
303      6.90     1.0  7.848E-03
304      6.80     2.3  7.200E-03
305      6.60     5.4  6.091E-03
306      6.40     8.8  5.098E-03
307      6.20    13.2  4.176E-03
308      6.00    18.2  3.442E-03
309      5.80    24.8  2.822E-03
310      5.60    33.3  2.318E-03
311      5.40    44.0  1.886E-03
312      5.20    57.0  1.570E-03
313      5.00    73.0  1.267E-03
314      4.80    96.0  1.037E-03
315      4.60   125.0  8.352E-04
316      4.40   163.0  6.768E-04
317      4.20   210.0  5.429E-04
318      4.00   274.0  4.378E-04
319      3.80   358.0  3.499E-04
320      3.60   462.0  2.794E-04
321      3.40   600.0  2.218E-04
322      3.20   790.0  1.735E-04
323      3.00  1030.0  1.354E-04
324      2.80  1320.0  1.022E-04
325      2.60  1740.0  7.488E-05
326      2.40  2240.0  5.322E-05
327      2.20  3000.0  3.686E-05
328      2.00  4000.0  2.506E-05
329      1.80  5480.0  1.656E-05
330      1.60  7500.0  1.094E-05
331      1.50  9000.0  8.784E-06
400      0.65  3.0E-04  6.0
401      6  10  1.0  4
402       365  3.0  26.0
403       730  2.0  28.0
404      1095  2.0  29.0
405      1460  1.0  30.0
```

3. Below are the calculation results after 2 years. A total of 6.0 ft of dredged material has been deposited. Results for the compressible foundation are not shown.

●●●●●●●●●●●●●●●●●●●●CURRENT CONDITIONS IN DREDGED FILL●●●●●●●●●●●●●●●●●●●●

●●●●● COORDINATES ●●●●●			●●●●● VOID RATIOS ●●●●●		
A	XI	Z	EINITIAL	E	EFINAL
6.0000	5.2510	0.7500	7.0000	7.0000	7.0000
5.5000	4.7628	0.6875	7.0000	6.6610	6.5162
5.0000	4.2904	0.6250	7.0000	6.4651	6.1820
4.5000	3.8289	0.5625	7.0000	6.3076	5.9311
4.0000	3.3764	0.5000	7.0000	6.1735	5.7405
3.5000	2.9319	0.4375	7.0000	6.0540	5.5829
3.0000	2.4945	0.3750	7.0000	5.9439	5.4565
2.5000	2.0638	0.3125	7.0000	5.8405	5.3419
2.0000	1.6393	0.2500	7.0000	5.7422	5.2369
1.5000	1.2209	0.1875	7.0000	5.6478	5.1447
1.0000	0.8083	0.1250	7.0000	5.5561	5.0594
0.5000	0.4013	0.0625	7.0000	5.4661	4.9820
0.	0.	0.	7.0000	5.3773	4.9226

	●●●●● STRESSES ●●●●●		●●●●● PORE PRESSURES ●●●●●		
XI	TOTAL	EFFECTIVE	TOTAL	STATIC	EXCESS
5.2510	58.9769	-0.0000	58.9769	58.9769	0.
4.7628	96.2629	4.4541	91.8089	89.4379	2.3709
4.2904	132.5688	7.6939	124.8749	118.9188	5.9561
3.8289	168.1906	10.8330	157.3578	147.7158	9.6420
3.3764	203.2485	13.8613	189.3872	175.9495	13.4387
2.9319	237.8135	16.8505	220.9630	203.6885	17.2745
2.4945	271.9318	20.0528	251.8790	230.9818	20.8972
2.0638	305.6344	23.4632	282.1712	257.8594	24.3118
1.6393	338.9444	27.2259	311.7185	284.3444	27.3741
1.2209	371.8787	31.1940	340.6847	310.4537	30.2310
0.8083	404.4505	35.5724	368.8781	336.2005	32.6776
0.4013	436.6682	40.4323	396.2359	361.5932	34.6427
0.	468.5374	45.4778	423.0596	386.6374	36.4222

TIME = 0.7300E 03 DEGREE OF CONSOLIDATION = 0.708691

SETTLEMENT = 0.7490 FINAL SETTLEMENT = 1.0569

BOTTOM BOUNDARY GRADIENT = -23.1737

WATER LEVEL ABOVE BOTTOM = 6.1961

4. **This page and the next contain the results after 8 years of consolidation. A total of 14.0 ft of dredged fill has been deposited.**

*******************CURRENT CONDITIONS IN DREDGED FILL*******************

***** COORDINATES *****			***** VOID RATIOS *****		
A	XI	Z	EINITIAL	E	EFINAL
14.0000	11.3111	1.7500	7.0000	7.0000	7.0000
13.5000	10.8250	1.6875	7.0000	6.6041	6.5162
13.0000	10.3570	1.6250	7.0000	6.3826	6.1820
12.5000	9.9011	1.5625	7.0000	6.2142	5.9311
12.0000	9.4545	1.5000	7.0000	6.0802	5.7405
11.5000	9.0155	1.4375	7.0000	5.9696	5.5829
11.0000	8.5830	1.3750	7.0000	5.8756	5.4565
10.5000	8.1559	1.3125	7.0000	5.7934	5.3419
10.0000	7.7326	1.2500	7.0000	5.7196	5.2369
9.5000	7.3158	1.1875	7.0000	5.6520	5.1447
9.0000	6.9020	1.1250	7.0000	5.5892	5.0594
8.5000	6.4920	1.0625	7.0000	5.5298	4.9820
8.0000	6.0857	1.0000	7.0000	5.4729	4.9226
7.5000	5.6829	0.9375	7.0000	5.4179	4.8632
7.0000	5.2834	0.8750	7.0000	5.3646	4.8039
6.5000	4.8873	0.8125	7.0000	5.3127	4.7560
6.0000	4.4943	0.7500	7.0000	5.2620	4.7090
5.5000	4.1045	0.6875	7.0000	5.2123	4.6619
5.0000	3.7178	0.6250	7.0000	5.1640	4.6148
4.5000	3.3340	0.5625	7.0000	5.1171	4.5754
4.0000	2.9531	0.5000	7.0000	5.0718	4.5395
3.5000	2.5750	0.4375	7.0000	5.0278	4.5036
3.0000	2.1996	0.3750	7.0000	4.9851	4.4676
2.5000	1.8268	0.3125	7.0000	4.9436	4.4317
2.0000	1.4566	0.2500	7.0000	4.9033	4.3966
1.5000	1.0889	0.1875	7.0000	4.8641	4.3676
1.0000	0.7236	0.1250	7.0000	4.8259	4.3385
0.5000	0.3606	0.0625	7.0000	4.7886	4.3095
0.	0.	0.	7.0000	4.7519	4.2804

XI	STRESSES TOTAL	STRESSES EFFECTIVE	PORE PRESSURES TOTAL	PORE PRESSURES STATIC	PORE PRESSURES EXCESS
11.3111	75.3995	-0.0000	75.3995	75.3995	0.
10.8250	112.5595	5.3362	107.2232	105.7345	1.4888
10.3570	148.5882	9.1834	139.4047	134.9382	4.4666
9.9011	183.8632	12.8882	170.9750	163.3882	7.5868
9.4545	218.5535	16.1951	202.3584	191.2535	11.1049
9.0155	252.7694	19.2020	233.5673	218.6444	14.9230
8.5830	286.5881	22.3060	264.2821	245.6381	18.6440
8.1559	320.0644	25.0774	294.9871	272.2894	22.6977
7.7335	353.2375	28.1767	325.0607	298.6375	26.4232
7.3158	386.1354	31.0139	355.1215	324.7104	30.4111
6.9020	418.7796	33.7812	384.9984	350.5296	34.4688
6.4920	451.1859	36.9892	414.1968	376.1109	38.0858
6.0857	483.3655	40.0640	443.3015	401.4655	41.8360
5.6829	515.3270	43.0321	472.2950	426.6020	45.6930
5.2834	547.0774	46.3021	500.7754	451.5274	49.2479
4.9873	578.6226	49.6774	528.9451	476.2476	52.6976
4.4943	609.9678	52.9724	556.9954	500.7678	56.2276
4.1045	641.1173	56.1978	584.9196	525.0923	59.8272
3.7178	672.0756	59.8826	612.1931	549.2256	62.9674
3.3340	702.8483	63.6297	639.2185	573.1733	66.0453
2.9531	733.4412	67.2576	666.1836	596.9412	69.2424
2.5750	763.8599	70.7771	693.0828	620.5349	72.5479
2.1996	794.1096	74.7173	719.3922	643.9596	75.4327
1.8268	824.1951	79.4859	744.7092	667.2201	77.4891
1.4566	854.1212	84.1177	770.0035	690.3212	79.6823
1.0889	883.8924	88.6252	795.2672	713.2674	81.9998
0.7236	913.5127	93.0187	820.4940	736.0627	84.4313
0.3606	942.9857	97.6540	845.3317	758.7108	86.6209
0.	972.3146	102.9677	869.3469	781.2146	88.1323

TIME = 0.2920E 04 DEGREE OF CONSOLIDATION = 0.768640

SETTLEMENT = 2.6889 FINAL SETTLEMENT = 3.4982

BOTTOM BOUNDARY GRADIENT = -28.3387

WATER LEVEL ABOVE BOTTOM = 12.5195

5. After 14 years, conditions in the dredged fill layer are as shown below and on the next page.

*******************CURRENT CONDITIONS IN DREDGED FILL*******************

***** COORDINATES *****			***** VOID RATIOS *****		
A	XI	Z	EINITIAL	E	EFINAL
14.0000	10.8073	1.7500	7.0000	7.0000	7.0000
13.5000	10.3252	1.6875	7.0000	6.4902	6.5162
13.0000	9.8664	1.6250	7.0000	6.2046	6.1820
12.5000	9.4231	1.5625	7.0000	5.9901	5.9311
12.0000	8.9916	1.5000	7.0000	5.8239	5.7405
11.5000	8.5694	1.4375	7.0000	5.6904	5.5829
11.0000	8.1549	1.3750	7.0000	5.5784	5.4565
10.5000	7.7468	1.3125	7.0000	5.4812	5.3419
10.0000	7.3445	1.2500	7.0000	5.3945	5.2369
9.5000	6.9474	1.1875	7.0000	5.3161	5.1447
9.0000	6.5549	1.1250	7.0000	5.2447	5.0594
8.5000	6.1666	1.0625	7.0000	5.1791	4.9820
8.0000	5.7823	1.0000	7.0000	5.1192	4.9226
7.5000	5.4016	0.9375	7.0000	5.0642	4.8633
7.0000	5.0242	0.8750	7.0000	5.0134	4.8039
6.5000	4.6499	0.8125	7.0000	4.9661	4.7560
6.0000	4.2784	0.7500	7.0000	4.9218	4.7090
5.5000	3.9096	0.6875	7.0000	4.8802	4.6619
5.0000	3.5433	0.6250	7.0000	4.8407	4.6148
4.5000	3.1795	0.5625	7.0000	4.8031	4.5754
4.0000	2.8179	0.5000	7.0000	4.7671	4.5395
3.5000	2.4586	0.4375	7.0000	4.7322	4.5035
3.0000	2.1014	0.3750	7.0000	4.6985	4.4676
2.5000	1.7462	0.3125	7.0000	4.6657	4.4317
2.0000	1.3931	0.2500	7.0000	4.6337	4.3966
1.5000	1.0420	0.1875	7.0000	4.6026	4.3676
1.0000	0.6928	0.1250	7.0000	4.5721	4.3385
0.5000	0.3455	0.0625	7.0000	4.5423	4.3095
0.	0.	0.	7.0000	4.5131	4.2804

	◆◆◆◆◆ STRESSES ◆◆◆◆◆		◆◆◆◆◆ PORE PRESSURES ◆◆◆◆◆		
XI	TOTAL	EFFECTIVE	TOTAL	STATIC	EXCESS
10.8073	120.0790	-0.0000	120.0790	120.0790	0.
10.3252	156.9912	7.2659	149.7253	150.1662	-0.4409
9.9664	192.4441	13.0999	179.3443	178.7941	0.5501
9.4231	226.9297	18.5267	208.4030	206.4547	1.9483
8.9916	260.6797	24.0098	236.6699	233.3797	3.2902
8.5694	293.8490	29.4047	264.4443	259.7240	4.7203
8.1549	326.5427	34.3643	292.1784	285.5927	6.5857
7.7468	358.8301	39.6160	319.2141	311.0551	8.1590
7.3445	390.7597	44.3596	346.4000	336.1597	10.2404
6.9474	422.3678	49.4526	372.9152	360.9428	11.9724
6.5549	453.6843	54.0969	399.5875	385.4343	14.1532
6.1666	484.7339	58.6691	426.0647	409.6589	16.4059
5.7833	515.5388	63.4649	452.0739	433.6388	18.4351
5.4016	546.1200	67.8614	478.2586	457.3951	20.8636
5.0242	576.4952	71.9285	504.5667	480.9452	23.6215
4.6499	606.6791	76.9004	529.7787	504.3041	25.4746
4.2784	636.6846	81.9897	554.6949	527.4846	27.2103
3.9096	666.5228	86.7807	579.7421	550.4978	29.2443
3.5433	696.2028	91.3184	604.8844	573.3528	31.5316
3.1795	725.7327	95.6393	630.0935	596.0577	34.0357
2.8179	755.1192	100.7739	654.3453	618.6192	35.7261
2.4586	784.3675	105.8260	678.5415	641.0425	37.4990
2.1014	813.4821	110.7218	702.7602	663.3321	39.4282
1.7462	842.4668	115.4777	726.9892	685.4918	41.4973
1.3931	871.3254	120.1077	751.2178	707.5254	43.6923
1.0420	900.0610	124.6242	775.4369	729.4360	46.0008
0.6928	928.6766	130.2925	798.3841	751.2265	47.1575
0.3455	957.1746	135.9580	821.2166	772.8996	48.3170
0.	985.5574	141.5151	844.0424	794.4574	49.5849

TIME = 0.5110E 04   DEGREE OF CONSOLIDATION = 0.912656

SETTLEMENT = 3.1927   FINAL SETTLEMENT = 3.4982

BOTTOM BOUNDARY GRADIENT = -22.4465

WATER LEVEL ABOVE BOTTOM = 12.7317

6. The input data file for the soft compressible layer example is given below.

```
100      11   1   2
101       1   3
200      2.80   20.0   21.0   36   75.0   500.0
201      3.00      0.0  1.210E-03
202      2.95      4.2  1.112E-03
203      2.90      8.8  1.030E-03
204      2.85     14.0  9.494E-04
205      2.80     19.6  8.854E-04
206      2.75     25.4  8.234E-04
207      2.70     32.0  7.616E-04
208      2.65     39.0  7.000E-04
209      2.60     48.0  6.392E-04
210      2.55     58.0  5.788E-04
211      2.50     70.0  5.227E-04
212      2.45     86.0  4.680E-04
213      2.40    104.0  4.234E-04
214      2.35    128.0  3.830E-04
215      2.30    154.0  3.456E-04
216      2.25    190.0  3.096E-04
217      2.20    232.0  2.736E-04
218      2.15    288.0  2.448E-04
219      2.10    344.0  2.160E-04
220      2.05    420.0  1.944E-04
221      2.00    510.0  1.714E-04
222      1.95    640.0  1.512E-04
223      1.90    780.0  1.325E-04
224      1.85    950.0  1.170E-04
225      1.80   1160.0  1.034E-04
226      1.75   1400.0  9.000E-05
227      1.70   1700.0  7.720E-05
228      1.65   2040.0  6.624E-05
229      1.60   2540.0  5.832E-05
230      1.55   3100.0  5.112E-05
231      1.50   3750.0  4.392E-05
232      1.45   4600.0  3.773E-05
233      1.40   5540.0  3.197E-05
234      1.35   6800.0  2.736E-05
235      1.30   8400.0  2.333E-05
236      1.25  10400.0  1.987E-05
300      0   0   0   1   0   62.4
301      0   0   0
400      0.6   1.0E-03   1.0
401      0   10   1.0   3
402       365   500.0   21.0
403       730   500.0   21.0
404      1095   0.0     21.0
```

7. Conditions in the compressible layer after 3 years are shown below. The total layer depth differs from the input value slightly due to the iterative method of calculating the material coordinate and the fact that Lagrangian coordinates are reset to match the material coordinate.

**************CURRENT CONDITIONS IN COMPRESSIBLE FOUNDATION*************

***** COORDINATES *****			***** VOID RATIOS *****		
A	XI	Z	EINITIAL	E	EFINAL
19.9525	18.5992	6.4879	2.4844	1.7208	1.7208
17.7837	16.7999	5.8391	2.3118	1.8267	1.7087
15.6692	14.9337	5.1903	2.2134	1.9213	1.6969
13.6065	13.0164	4.5415	2.1450	1.9817	1.6862
11.5864	11.0745	3.8928	2.0852	1.9970	1.6755
9.5993	9.1359	3.2440	2.0392	1.9744	1.6648
7.6415	7.2203	2.5952	1.9991	1.9274	1.6541
5.7047	5.3413	1.9464	1.9711	1.8627	1.6455
3.7861	3.5083	1.2976	1.9436	1.7858	1.6382
1.8348	1.7279	0.6488	1.9176	1.7027	1.6309
0.	0.	0.	1.8930	1.6258	1.6236

	***** STRESSES *****		***** PORE PRESSURES *****		
XI	TOTAL	EFFECTIVE	TOTAL	STATIC	EXCESS
18.5992	1724.8102	1575.0000	149.8102	149.8102	-0.0000
16.7999	1909.9566	1047.8234	862.1332	262.0843	600.0489
14.9337	2099.2790	720.3325	1378.9465	378.5344	1000.4121
13.0164	2291.7961	557.5811	1734.2150	498.1792	1236.0358
11.0745	2485.8404	517.9196	1967.9208	619.3512	1348.5696
9.1359	2679.6824	576.6408	2103.0416	740.3209	1362.7207
7.2203	2872.0877	703.3944	2168.6934	859.8540	1308.8394
5.3413	3062.2064	906.7564	2155.4501	977.1003	1178.3498
3.5083	3249.4594	1228.2871	2021.1713	1091.4800	929.6913
1.7279	3433.4306	1683.6487	1749.7819	1202.5799	547.2020
0.	3614.1230	2292.1446	1331.9784	1310.4000	21.5784

TIME = 0.1095E 04   DEGREE OF CONSOLIDATION = 0.516565

SETTLEMENT = 1.3833   FINAL SETTLEMENT = 2.6774

BOTTOM BOUNDARY GRADIENT = 909.1478

WATER LEVEL ABOVE BOTTOM = 21.0000

8. Compressible layer conditions after 6 years are shown below.

◆◆◆◆◆◆◆◆◆◆◆◆◆◆CURRENT CONDITIONS IN COMPRESSIBLE FOUNDATION◆◆◆◆◆◆◆◆◆◆◆◆◆

◆◆◆◆◆ COORDINATES ◆◆◆◆◆			◆◆◆◆◆ VOID RATIOS ◆◆◆◆◆		
A	XI	Z	EINITIAL	E	EFINAL
19.9825	17.9417	6.4879	2.4844	1.7208	1.7208
17.7837	16.1632	5.8391	2.3118	1.7615	1.7087
15.6692	14.3596	5.1903	2.2134	1.7970	1.6970
13.6065	12.5362	4.5415	2.1450	1.8217	1.6862
11.5264	10.7016	3.8928	2.0852	1.8308	1.6755
9.5993	8.8668	3.2440	2.0392	1.8221	1.6649
7.6415	7.0431	2.5952	1.9991	1.7972	1.6541
5.7047	5.2398	1.9464	1.9711	1.7601	1.6455
3.7861	3.4633	1.2976	1.9436	1.7154	1.6382
1.8848	1.7168	0.6485	1.9176	1.6686	1.6309
0.	0.	0.	1.8930	1.6248	1.6236

	◆◆◆◆◆ STRESSES ◆◆◆◆◆		◆◆◆◆◆ PORE PRESSURES ◆◆◆◆◆		
XI	TOTAL	EFFECTIVE	TOTAL	STATIC	EXCESS
17.9417	1765.8365	1575.0201	190.8165	190.8365	-0.0201
16.1632	1949.6999	1344.8958	604.7940	301.8178	302.9763
14.3596	2135.1075	1174.5330	960.5745	414.3622	546.2123
12.5362	2321.7578	1068.6232	1252.9346	528.1404	724.7942
10.7016	2509.1119	1030.6548	1478.4571	642.6224	835.8347
8.8668	2696.4732	1067.0027	1629.4705	757.1116	872.3589
7.0431	2883.1429	1173.3985	1709.7444	870.9092	838.8352
5.2398	3068.5421	1351.6883	1716.8537	983.4363	733.4174
3.4633	3252.2670	1607.7970	1644.4700	1094.2880	550.1820
1.7168	3434.1201	1913.7976	1520.3225	1203.2693	317.0532
0.	3614.1232	2292.0714	1322.0518	1310.4000	11.6517

TIME = 0.2190E 04   DEGREE OF CONSOLIDATION = 0.762221

SETTLEMENT = 2.0408   FINAL SETTLEMENT = 2.6774

BOTTOM BOUNDARY GRADIENT = 491.8586

WATER LEVEL ABOVE BOTTOM = 21.0000

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Cargill, Kenneth W.
Consolidation of soft layers by finite strain analysis / by Kenneth W. Cargill (Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; Springfield, Va. : available from NTIS, 1982.
113 p. in various pagings ; ill. ; 27 cm. -- (Miscellaneous paper ; GL-82-3)
Cover title.
"March 1982."
Final report.
"Prepared for Office, Chief of Engineers, U.S. Army under CWIS Work Unit No. 31173, Task 34."
Bibliography: p. 63-64.

1. Computer programs. 2. CSLFS (Computer program). 3. Difference equations, Nonlinear. 4. Soil consolidation. I. United States. Army. Corps of Engineers. Office of the Chief of Engineers. II. U.S. Army Engineer Waterways

Cargill, Kenneth W.
Consolidation of soft layers by finite strain : ... 1982.
(Card 2)

Experiment Station. Geotechnical Laboratory. III. Title IV. Series: Miscellaneous paper (U.S. Army Engineer Waterways Experiment Station) ; GL-82-3.
TA7.W34m no.GL-82-3


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